Appendix C

PERTINENT STANDARDS

PERTINENT STANDARDS

The standards related to the measurement and definition of radio noise, conducted noise, and electromagnetic fields are listed in this appendix.

STANDARDS RELATED TO THE MEASUREMENT OF RADIO NOISE

American National Standards Institute

1. ANSI C63.2 - 1980, Specifications for Electromagnetic Noise and Field-strength Instrumentation, 10 kHz to 1 GHz.

2. ANSI C63.3 - 1964, Standard Radio Noise and Field Strength Meters, 20 MHz to 1 GHz.

3. ANSI C63.4 - 1981, Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 10 kHz to 1 GHz.

4. ANSI C93.3 - 1981, Requirements for Power Line Carrier Line Traps.

5. IEC, CISPAR Publication 16-1977, Specifications for Radio Interference Measuring Apparatus and Measurement Methods.

Institute Of Electrical and Electronics Engineers

1. ANSI/IEEE 213-1961 (Reaffirmed 1974), Radio Interference: Methods of Measurement of Conducted Interference Output to the Power Line From FM and Television Broadcast Receivers in the Range of 300 kHz to 25 MHz

2. IEEE 214-1961, Construction Drawings of Line Impedance Network Required for the Measurement of Conducted Interference to the Power Line from FM and Television Receivers in the Range of 300 kHz to 25 MHz.

3. IEEE 263-1965, Measurement of Radio Noise Generated By Motor Vehicles and affecting Mobile Communications Receivers in the Frequency Range of 25 to 1000 MHz.

4. ANSI/IEEE, Measurement of Electrical Noise and the Harmonic Filter Performance of High-Voltage Direct Current Systems.

5. IEEE 376-1975, Standard for the Measurement of Impulse Strength and Impulse Bandwidth.

6. ANSI/IEEE 430-1976, Procedures for the Measurement of Radio Noise from Overhead Power Lines.

7. IEEE 469-1977, Recommended Practice for Voice Frequency Electrical-Noise Tests of Distribution Transformers.

8. IEEE 518-1977, A Guide for Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources.

9. IEEE 539-1979, Definitions of Terms Relating to Overhead Power Line Corona and Radio Noise.

STANDARDS RELATING TO ELECTRIC AND MAGNETIC FIELD MEASUREMENTS, INTERFERENCE, AND ELECTROMAGNETIC COMPATIBILITY

American National Standards Institute

1. ANSI C63.12, Procedures for Control of and Recommended Practice on System Electromagnetic Compatibility.

2. IEC, CISPR (1978), Limits and Methods of Measurement of Radio Interference Characteristics of Vehicles, Motor Boats, and Spark-Ignited Engine Driven Devices, CISPR Publication 12.

Institute of Electrical and Electronics Engineers

1. ANSI/IEEE 644-1979, Recommended Practice for Measurement of Electric and Magnetic Fields from Power Lines.

2. IEEE 139-1952, Recommended Practice for Measurement of Field Intensity Above 300 MHz from Radio-Frequency Industrial, Scientific, and Medical Equipment.

3. IEEE 140-1950, Recommended Practice for Minimization of Interference from Radio- Frequency Heating Equipment.

4. IEEE 187-1951, Open-Field Method of Measurement of Spurious Radiation from Frequency Modulated and Television Broadcast Receivers.

5. IEEE 281-1968, Standard Service Conditions for Power System Communications Apparatus.

6. IEEE 291-1969, IEEE Standards Report on Measuring Field Strength in Radio Wave Propagation.

Department of Defense

1. MIL-STD-461B, Electromagnetic Emission and Susceptibility Requirements (1980).

2. MIL-STD-462, Electromagnetic Interference Characteristics (1967).

3. MIL-STD-826A, Electriomagnetic Interference Test Requirements and Test Methods (1966).

Other Sources

1. Society of Automotive Engineers Pub. APR 958, Broadband Electromagnetic Interference Measurement Antennas; Standard Calibration Requirements and Methods.

2. National Electrical Manufacturers Association (NEMA) No. 107-1964, Methods af Measurement of Radio Influence Voltage (RIV) of High-Voltage Apparatus.

ORGANIZATIONS CONCERNED WITH STANDARDS FOR POWER LINE INTERFERENCE

IEEE Power Engineering Society

1. Transmission and Distribution Committee

   a. Corona and Field Effects Subcommittee
   b. Radio Noise Working Group
   c. Working Group on the Harmonic Aspects of DC Systems
   d. Working Group on Power System Harmonics

2. Power System Communication Committee

   a. Carrier Subcommittee
   b. Wire Line Subcommittee
   c. Standards Subcommittee
   d. Methods of Measurement Subcommittee
   e. Microwave and Radio Subcommittee
   f. Research Subcommittee

IEEE Electromagnetic Compatibility Society

American National Standards Institute (ANSI)

1. ANSI C63.4, Subcommittee concerned with the Methods of Measurement of Radio Noise from Low Voltage Electrical and Electromics Equipment.

2. ANSI 63.2, Subcommittee Concerned with the Specification of Electromagnetic Noise and Field-strength Instrumentation over 10 kHz to 1 GHz.

3. ANSI C63.12, Subcommittee Concerned with Procedures for Control of and Recommended Practice on Electromagnetic Compatibility.

Commission E of International Union Of Radio Science (URSI)

Comite International Special Des Perturbations Radioelectiques (CISPR)

Note: ANSI acts as the sole agent in the United States for the International Organization for Standardization (ISO), the International Electro-technical Commission (IEC), and Comite International, Special des Perturbations Redioelectiques (CISPR).

EPRI EL/EM-4290, Volume 1

Below are five index cards that allow for filing according to the four cross-references in addition to the title of the report. A brief abstract describing the major subject area covered in the report is included on each card.

EPRI EL/EM-4290
Volume 1
RP2017-1
Final Report
October 1985

EPRI

Harmonics and Electrical Noise in Distribution Systems Volume 1: Measurements and Analyses

Contractor: SRI International

Characterization of the harmonics and electrical noise on distribution lines at 10 utilities showed that discrete harmonics of the power frequency are the noise most likely to impair distribution line carrier system performance. Sources of these harmonics are customer switching devices and nonlinear loads. The report describes mitigation methods for utilities and equipment manufacturers. 184 pp

EPRI Project Managers: W. E. Shula; W. E. Blair

Cross-References:
1. EPRI EL/EM-4290, Volume 1 2. RP2017-1 3. Distribution Program; Residential an Commercial Program 4. Noise

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, CA 94303 415-855-2000

EPRI EL/EM-4290, VOLUME 1

EPRI EL/EM-4290
Volume 1
RP2017-1
Final Report
October 1985

EPRI

Harmonics and Electrical Noise in Distribution Systems Volume 1: Measurements and Analyses

Contractor: SRI International

Characterization of the harmonics and electrical noise on distribution lines at 10 utilities showed that discrete harmonics of the power frequency are the noise most likely to impair distribution line carrier system performance. Sources of these harmonics are customer switching devices and nonlinear loads. The report describes mitigation methods for utilities and equipment manufacturers. 184 pp

EPRI Project Managers: W. E. Shula; W. E. Blair

Cross-References:
1. EPRI EL/EM-4290, Volume 1 2. RP2017-1 3. Distribution Program; Residential an Commercial Program 4. Noise

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, CA 94303 415-855-2000

RP2017-1

EPRI EL/EM-4290
Volume 1
RP2017-1
Final Report
October 1985

EPRI

Harmonics and Electrical Noise in Distribution Systems Volume 1: Measurements and Analyses

Contractor: SRI International

Characterization of the harmonics and electrical noise on distribution lines at 10 utilities showed that discrete harmonics of the power frequency are the noise most likely to impair distribution line carrier system performance. Sources of these harmonics are customer switching devices and nonlinear loads. The report describes mitigation methods for utilities and equipment manufacturers. 184 pp

EPRI Project Managers: W. E. Shula; W. E. Blair

Cross-References:
1. EPRI EL/EM-4290, Volume 1 2. RP2017-1 3. Distribution Program; Residential an Commercial Program 4. Noise

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, CA 94303 415-855-2000

DISTRIBUTION PROGRAM; RESIDENTIAL AND COMMERCIAL PROGRAM

EPRI EL/EM-4290
Volume 1
RP2017-1
Final Report
October 1985

EPRI

Harmonics and Electrical Noise in Distribution Systems Volume 1: Measurements and Analyses

Contractor: SRI International

Characterization of the harmonics and electrical noise on distribution lines at 10 utilities showed that discrete harmonics of the power frequency are the noise most likely to impair distribution line carrier system performance. Sources of these harmonics are customer switching devices and nonlinear loads. The report describes mitigation methods for utilities and equipment manufacturers. 184 pp.

EPRI Project Managers: W. E. Shula; W. E. Blair

Cross-References:
1. EPRI EL/EM-4290, Volume 1 2. RP2017-1 3. Distribution Program; Residential and Commercial Program 4. Noise

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, CA 94303 415-855-2000

NOISE

EPRI EL/EM-4290
Volume 1
RP2017-1
Final Report
October 1985

EPRI

Harmonics and Electrical Noise in Distribution Systems Volume 1: Measurements and Analyses

Contractor: SRI International

Characterization of the harmonics and electrical noise on distribution lines at 10 utilities showed that discrete harmonics of the power frequency are the noise most likely to impair distribution line carrier system performance. Sources of these harmonics are customer switching devices and nonlinear loads. The report describes mitigation methods for utilities and equipment manufacturers. 184 pp.

EPRI Project Managers: W. E. Shula; W. E. Blair

Cross-References:
1. EPRI EL/EM-4290, Volume 1 2. RP2017-1 3. Distribution Program; Residential and Commercial Program 4. Noise

ELECTRIC POWER RESEARCH INSTITUTE
Post Office Box 10412, Palo Alto, CA 94303 415-855-2000

Technical Memorandum
NPS9608

August 1996

EMI FROM A DESKTOP COMPUTER

Prepared For:

COMNAVSECGRU N-44
Fort George G. Meade, MD
Attention: Mrs. Jackie Sherry

Prepared By:

Wilbur R. Vincent
Robert M. Perry
Richard W. Adler

1. INTRODUCTION

A few cases of EMI at naval receiving sites have been traced to desktop computers. Since little data is available on the properties and magnitude of such EMI, preliminary measurements were made on a desktop computer to better understand the EMI source mechanisms.

A standard 486-25 clone computer was removed from a small receiving site. It was identified as a source of radio interference at the site. The computer components were installed in a standard desktop case with a metal base and a plastic cover. It was equipped with a standard 15-inch monitor, a keyboard, an internal modem card, and a standard LAN card. The computer was set up in an office environment, and it was connected to the LAN in the Electrical Engineering building at the Naval Postgraduate School.

Instrumentation employed by the COMNAVSECGRU Signal-to-Noise Enhancement Program (SNEP) Teams was used to measure EMI radiated from the computer and EMI current on cables connected to the computer over wide frequency bands. Some background ambient EMI current on the cables was encountered from other computer systems and devices operating in the building. This ambient current was identified, and it could be distinguished from that generated by the test computer.

The results provided in this memorandum are from only one computer. It was a well-used desktop computer considered to be typical of many of those used in naval receiving sites. However, the vast number of styles of desktop computers available on the open market, and the variations from one type to another, must be considered when reviewing the data presented in this memorandum. Nevertheless, the data indicate that EMI generated by standard desktop computers can be a significant factor adversely affecting the ability of a receiving site to detect radio signals.

2. TEST CONFIGURATION

The computer, monitor, and keyboard were installed on a standard wooden laboratory bench. Power was obtained from a nearby 120-V electrical outlet. A coaxial LAN cable (RG-58 type cable) about 60-ft long was run to an adjacent room containing another computer that was connected to the building's LAN network. The LAN cable could be connected or disconnected at this second computer installation.

Figure 2-1 shows a sketch of the test installation.

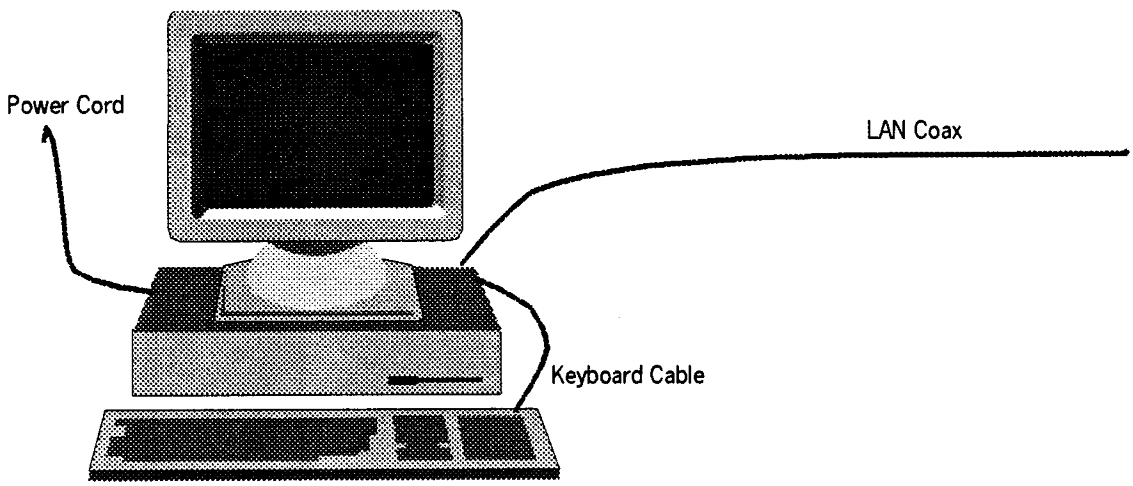


Figure 2-1

Sketch of Test Configuration

Since direct radiation from the computer was not a primary factor in the interference problem, EMI current flowing on the cables to and from the computer was considered to be a likely source of the interference. A Fisher Model F-70 Current Probe was used to examine EMI current on these conductors. The F-70 Current Probe provided accurate current measurements from 100 kHz up to 50 MHz, and it was a reasonable sensor of EMI current up to 100 MHz.

Figure 2-2 shows a block diagram of the instrumentation used to measure EMI current.

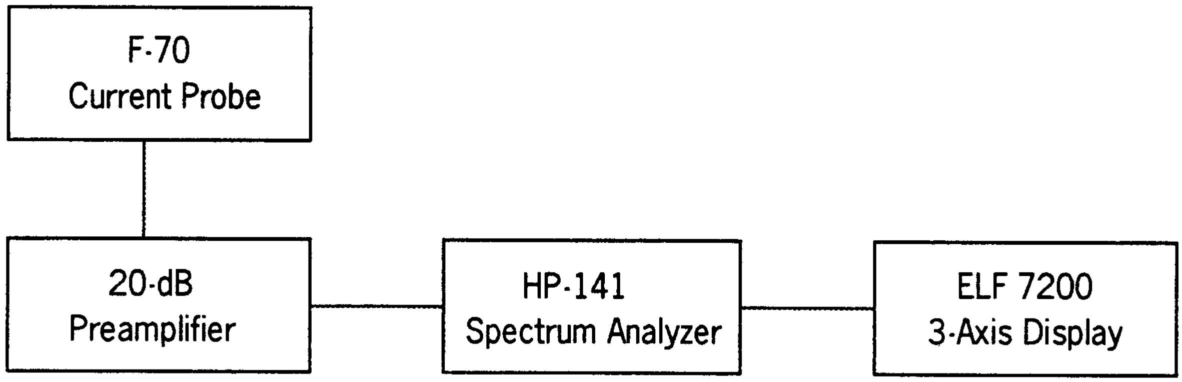


Figure 2-2

Block Diagram of Primary Instrumentation

A 20-dB preamplifier was used to amplify the probe's output signal to ensure that low-levels of EMI current could be examined. A HP-141 Series Spectrum Analyzer equipped with a 110-MHz RF head was used to measure EMI current over wide frequency bands. The analyzer was interfaced to an ELF Engineering Model 7200B 3-Axis Display. The display showed the temporal and spectral properties of the EMI, and it permitted the direct comparison of EMI current amplitudes for various test conditions.

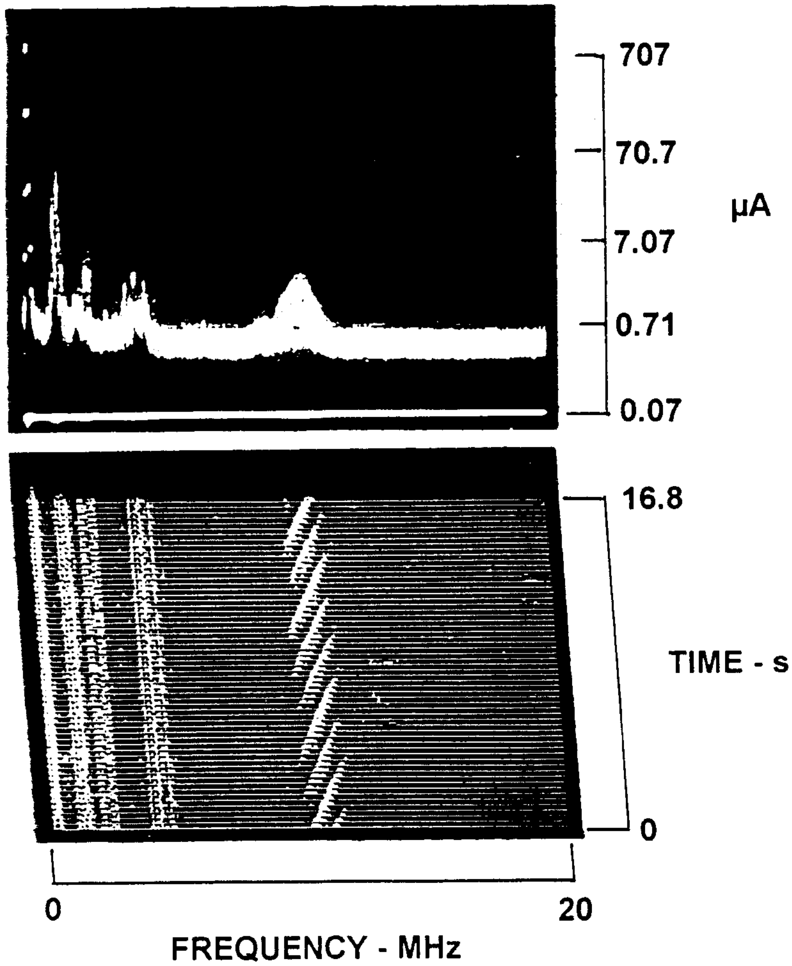
3. TEST RESULTS

Figure 3-1 (960517 1020) shows ambient EMI current flowing on the shield of the LAN cable with the computer and display turned off and the LAN cable disconnected from the building's LAN system. The useful frequency range of the view is 100 kHz up to 100 MHz. The small spectral component of current near 90 MHz is from a local FM broadcast station. No other significant ambient EMI current component was identified in this view except at very low frequencies where the spectral components were compressed into a small portion of the frequency scale.

Figure 3-2 (960517 1006) shows the ambient current on the LAN cable over the 100-kHz to 20-MHz frequency range. The distinct peak in current at about 10 MHz contained a combination of FM and AM modulation components synchronized to the power-line frequency. The source of this component of EMI is described later. The sources of the discrete-frequency spectral components at frequencies from 100 kHz up to about 5 MHz were not identified. They are believed to originate from other computers and digital equipment located elsewhere in the building.

The ambient current flowing on the LAN cable was generally below the level that would create harmful interference in a receiving site. The maximum value of current suggested by the SNEP program (2 μA from 100 kHz to 100 MHz for a small site and 10 μA for a large site) was exceeded only near 2.5 MHz. These spectral components probably originated from sources in the building.

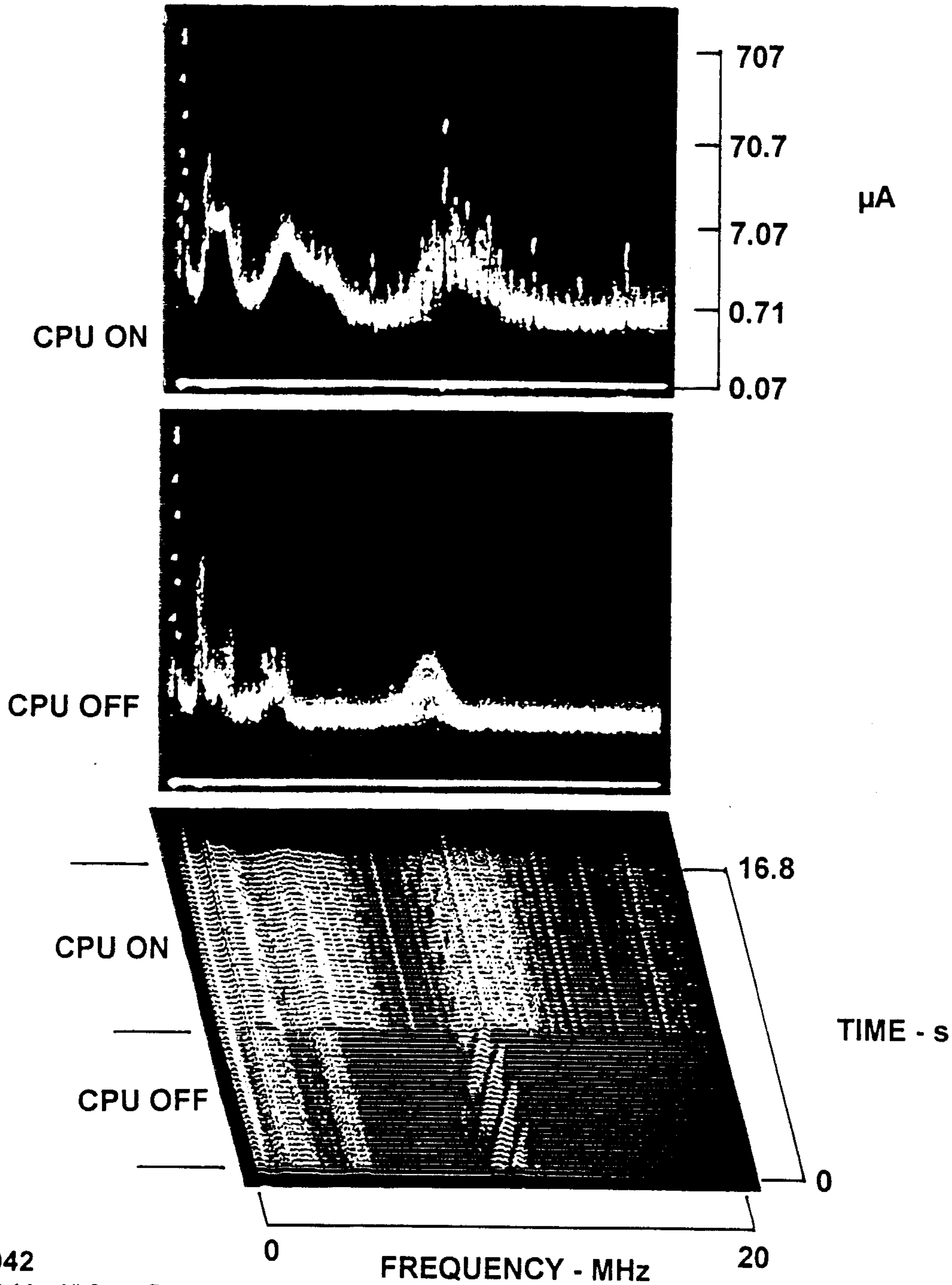
Figure 3-3 (960517 1042) shows EMI current flowing on the LAN cable shield when the computer is turned on and off. The LAN cable was still disconnected from the building's LAN system. The frequency range is from 100 kHz to 20 MHz, identical to the range used for the previous figure. A significant increase in EMI current occurred when the computer was turned on. A number of discrete-frequency components were injected into the 60-ft long LAN cable shield by the computer as well as lower levels of broad-band noise current. Several components exceeded the SNEP-suggested EMI current limits for both a small and a large site. The spectral structure of the computer-generated EMI current is similar to that of the ambient current. This suggests that the ambient current is probably from other digital devices operating in the building.



960517 1006
NPS, LAN Cable, 2" from Computer
CPU OFF, MON OFF, AMBIENT
10 MHz, 200 MHz, 30 kHz, 200 ms
F-70, +20, 0, -30

Figure 3-2

Ambient EMI Current on the LAN Cable, 0 to 20 MHz



960517 1042
NPS, LAN Cable, 2" from Computer
CPU ON/OFF
10 MHz, 20 MHz, 30 kHz, 200 ms
F-70, +20, 0, -30

Figure 3-3

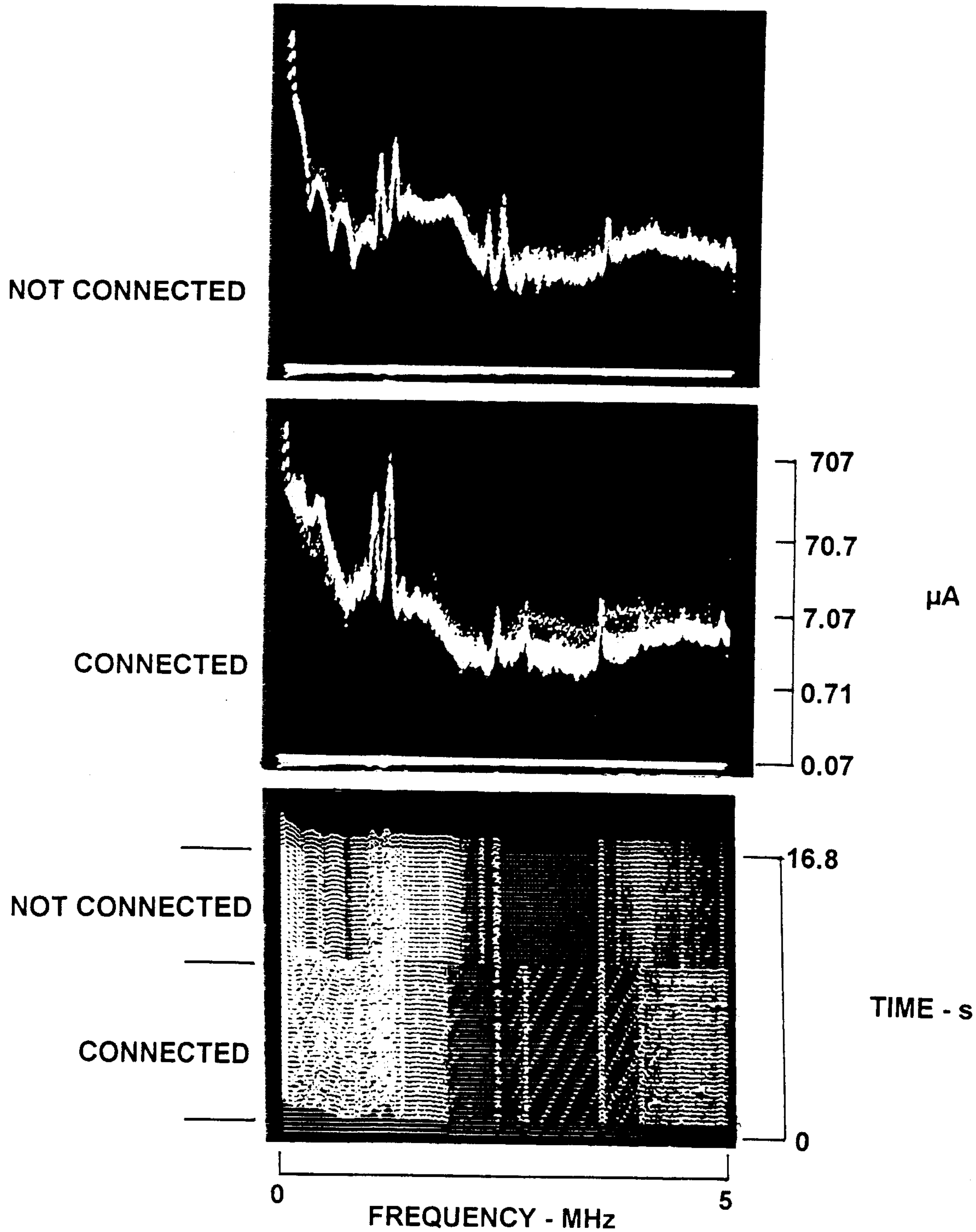
Comparison of Ambient and Operating EMI Current on LAN Cable, 0 to 20 MHz

Next, the test computer's LAN cable was connected to the building's LAN system. Figure 3-4 (960517 1120) shows EMI current flowing on the shield of the LAN coaxial cable when the cable was connected and disconnected from the LAN. The frequency range of the data is 100 kHz to 5 MHz. Significant changes were noted in the spectral and temporal structure of the EMI current for the two operating conditions. It is evident that the building's LAN system also carried significant levels of EMI shield current. The shield current for both conditions exceeded the SNEP-suggested levels. EMI current flowing on the outer surface of the shield of the long LAN cable is an obvious potential source of radiated EMI a receiving site.

Figure 3-5 (960517 1140) shows both the common-mode ambient current flowing on the keyboard cable and the EMI current when the computer was turned on. The view shows EMI current over the frequency range of 100 kHz to 100 MHz. The ambient current was very low except at frequencies below about 5 MHz, and it was similar to that found on the LAN cable shield. A significant increase in the EMI current occurred when the computer was turned on. Numerous discrete-frequency spectral components were noted along with lower levels of broad-band noise. The current exceeded SNEP-recommended levels although no interference was traced to this cable is the field. This is probably because the short length of the keyboard cable did not radiate sufficient levels of electromagnetic fields to cause noticeable interference to a receiver site.

Figure 3-6 (960517 1057) shows the common-mode EMI current flowing in the power cable when the computer was turned off and on. The frequency range of the data is 100 kHz to 100 MHz. Spectral components of EMI current when the computer is on are shown throughout the frequency range of the data. Three strong discrete-frequency components are shown at frequencies above 50 MHz. All three exceed the suggested limit of 2 μA for a small receiving site and the component near 50 MHz exceeds the suggested limit of 10 μA for a large site. A number of components exceed these limits at frequencies below 30 MHz.

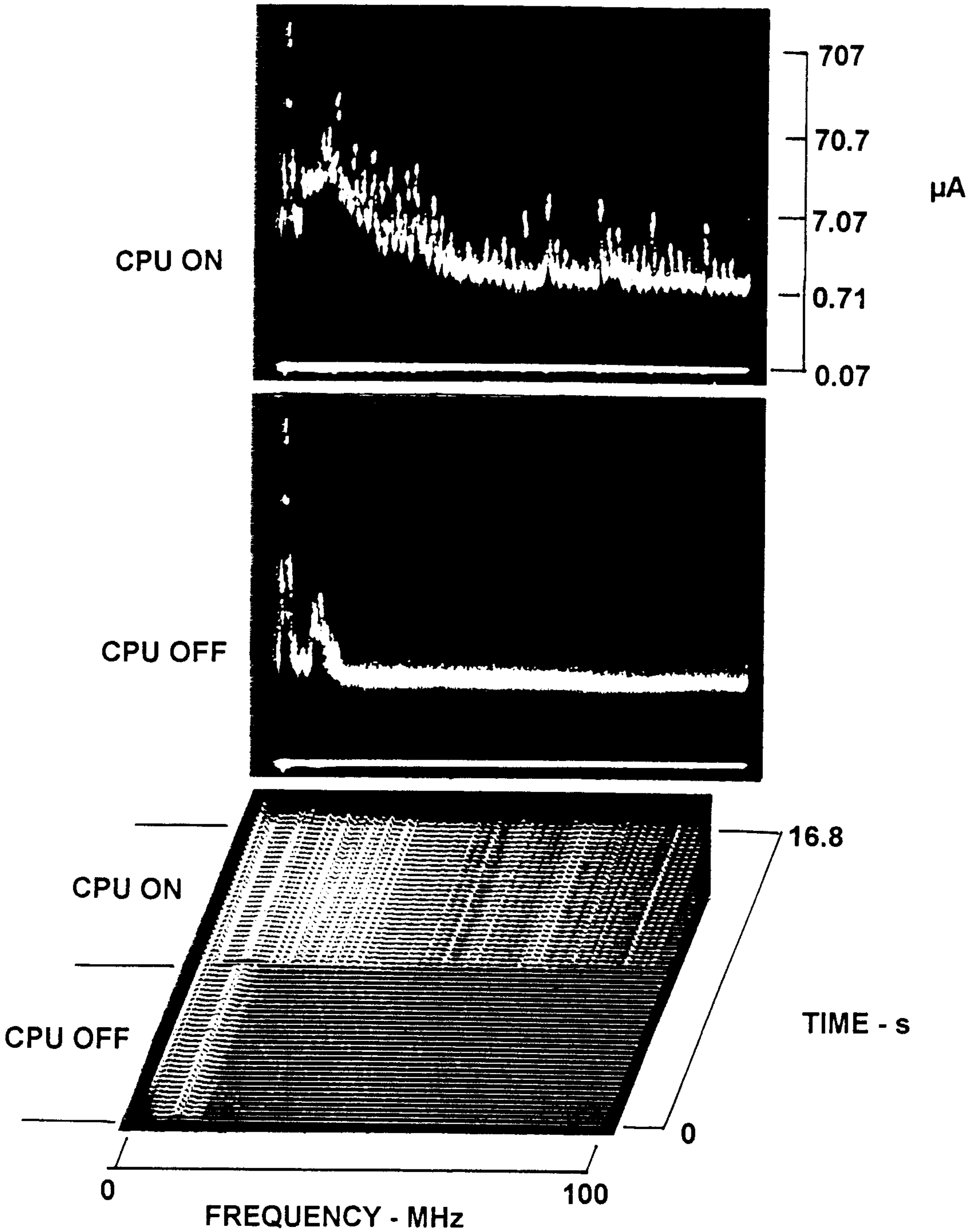
Figure 3-7 (960517 1106) shows the spectral and temporal structure of common-mode EMI current on the power cable over a frequency range of 100 kHz to 20 MHz. This figure provides an expanded view of the properties of the EMI current for the lower frequencies. The EMI current consists of a large number of discrete-frequency components along with lower level wide-band noise.



960517 1120
NPS, LAN Cable, 2" from Computer
2.5 MHz, 5 MHz, 30 kHz, 200 ms
F-70, +20, 0, -30
ECE LAN, Not connected/connected

Figure 3-4

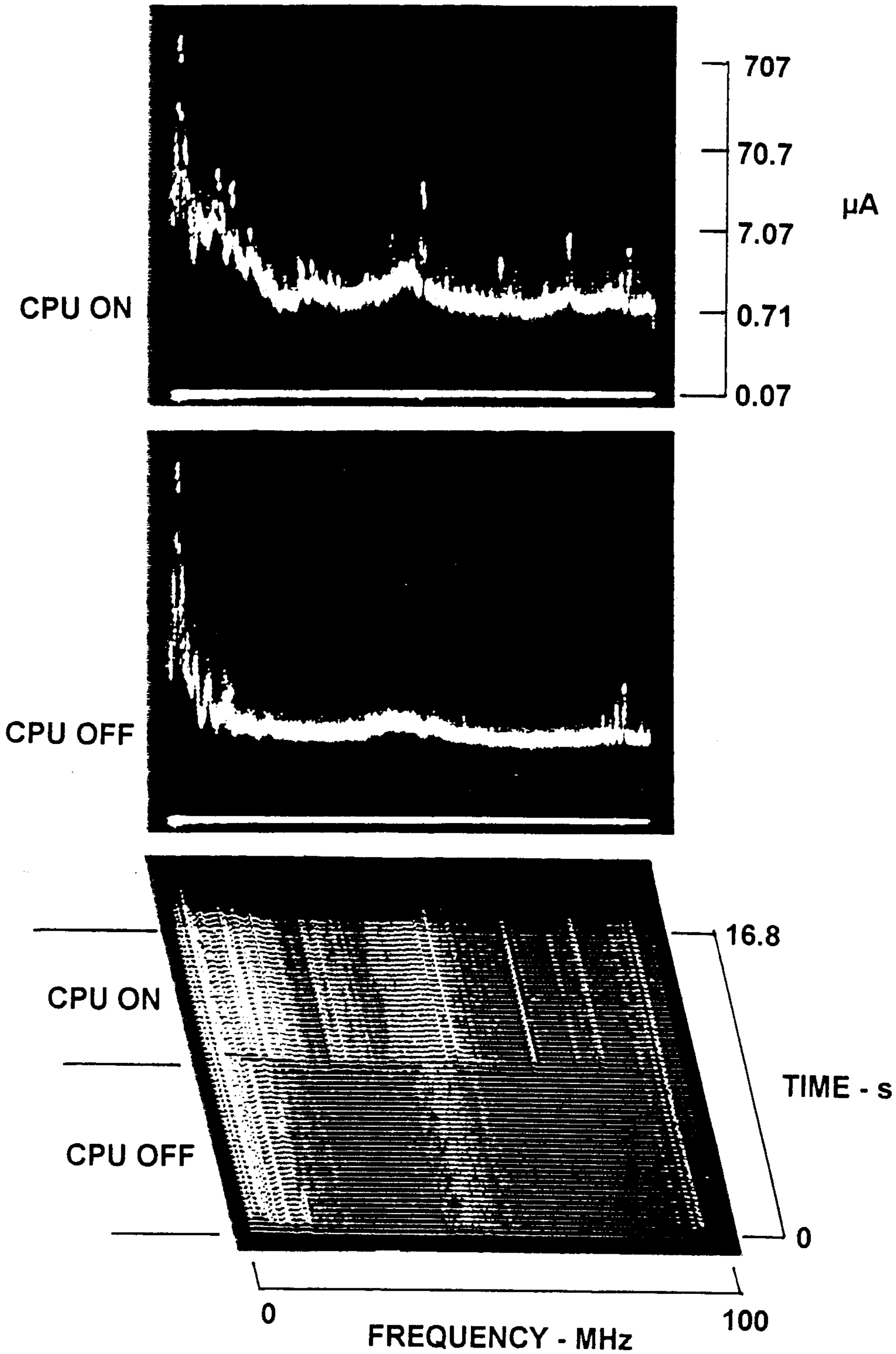
Comparison of EMI Current with the LAN Connected and Disconnected from the Building LAN



960517 1140
NPS, Keyboard Cable, CPU ON/OFF
50 MHz, 100 MHz, 300 kHz, 200 ms
F-70, +20, 0, -30

Figure 3-5

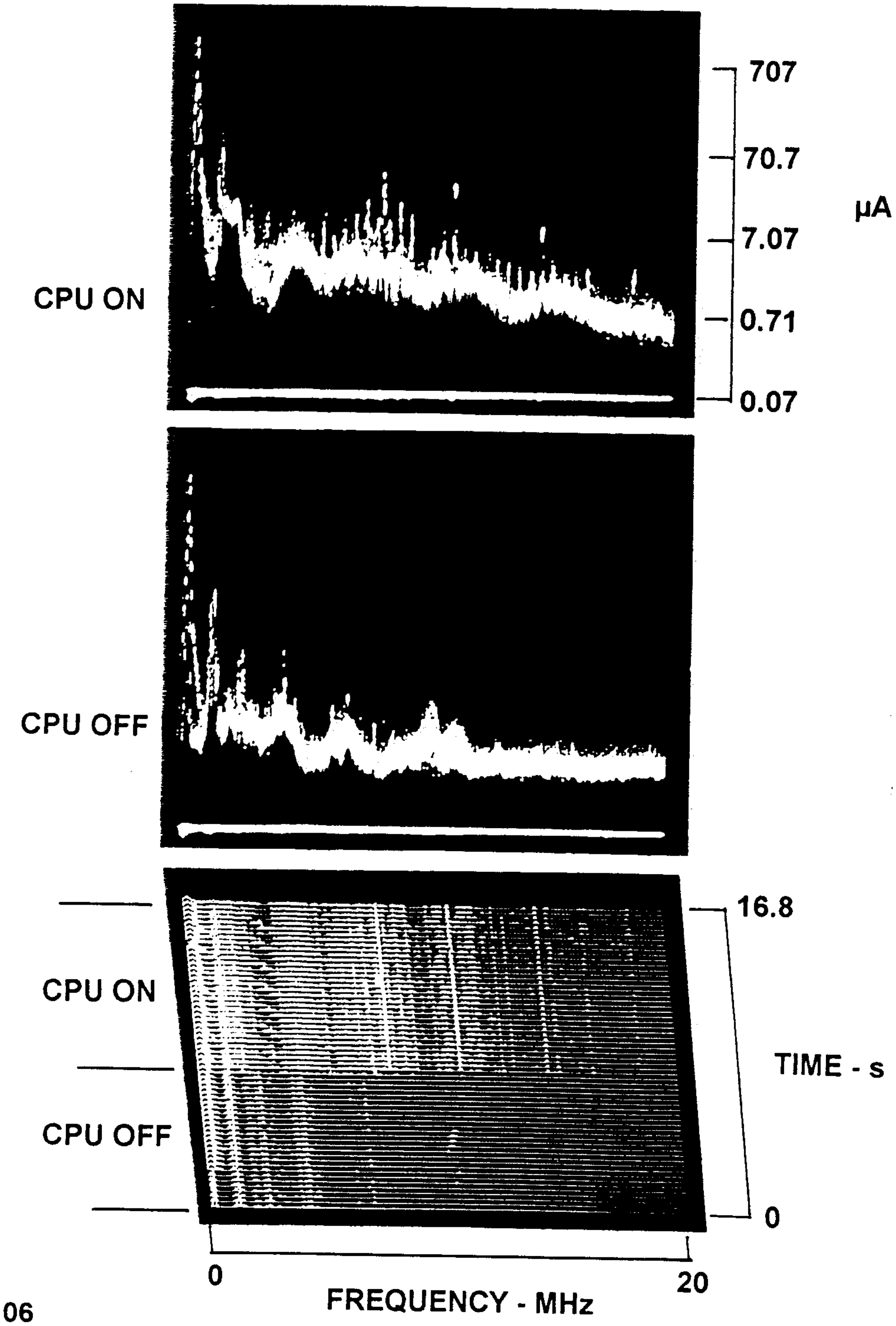
Ambient and Operating EMI Current on the Keyboard Cable



960517 1057
NPS, Power Cable, 2" from Computer
CPU ON/OFF
50 MHz, 100 MHz, 300 kHz, 200 ms
F-70, +20, 0, -30

Figure 3-6

Operating and Ambient Common-Mode EMI Current on the Power Cable, 100 kHz to 100 MHz



960517 1106
NPS, Power Cable, CPU ON/OFF
10 MHz, 20 MHz, 30 kHz, 200 ms
F-70, +20, 0, -30

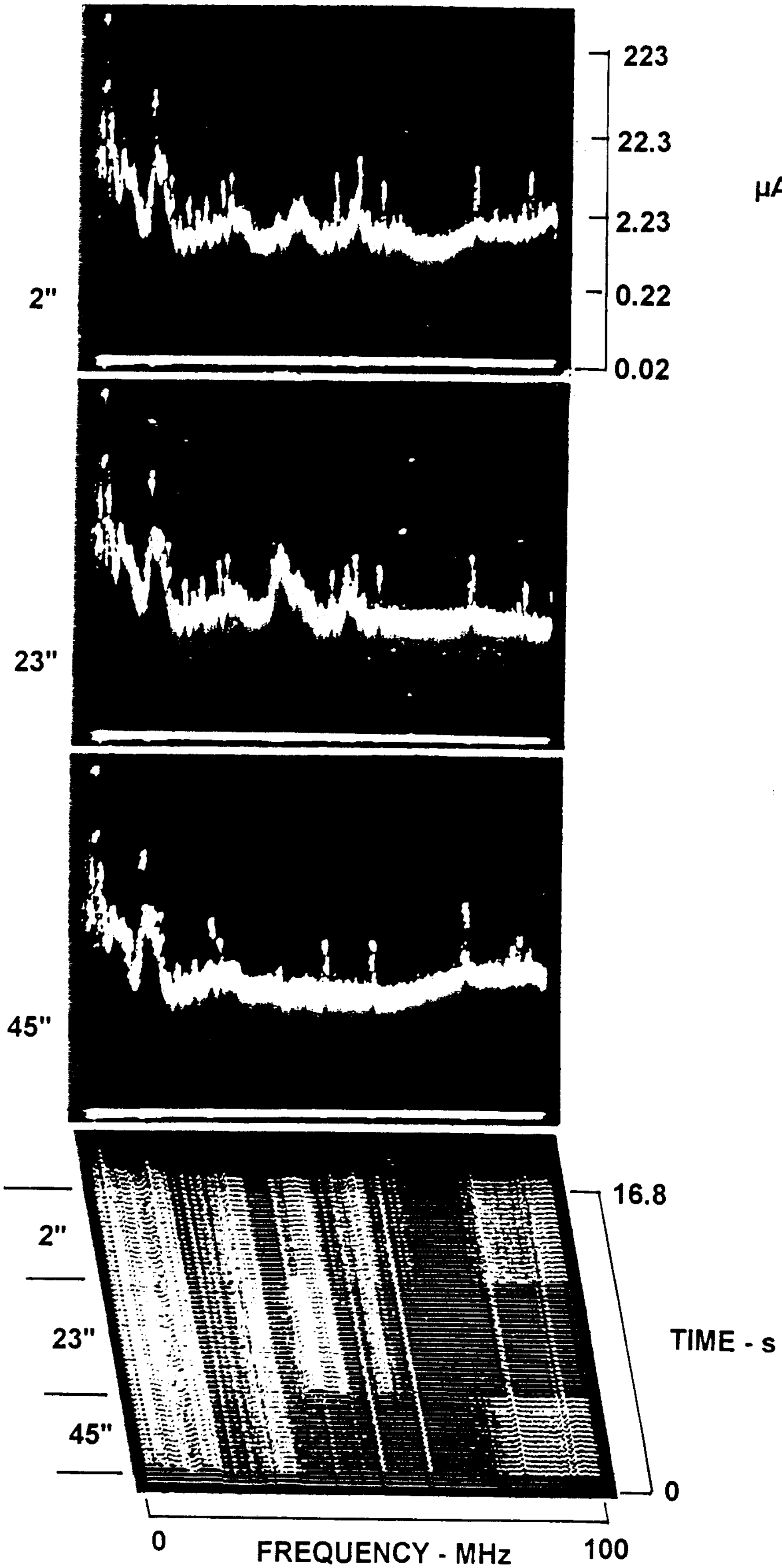
Figure 3-7

Operating and Ambient Common-Mode EMI Current on the Power Cable, 100 kHz to 20 MHz

Two additional examples of EMI current are provided to illustrate the difficulty in establishing simple guidelines to explain some of the findings. Figure 3-8 (960517 0944) shows the spectral shape of the EMI current at three locations along the LAN cable. The top amplitude-vs.-frequency view was obtained with the F-70 current probe located 3 inches from the computer. The middle view was obtained with the current probe 23 inches from the computer. The bottom amplitude-vs.-frequency view was obtained with the probe located 45 inches from the computer. Significant changes in the spectral components are shown.

The 3-axis presentation at the bottom of the figure shows data from all three locations. The amplitude has been compressed to allow the changes in spectral content of the EMI current to be compared for the three locations. Little change in the spectral content of the EMI current was noted at frequencies below about 20 MHz. The distance from the computer to the furthest measurement point (45 inches) is short compared to the long wavelengths of the EMI current at the lower frequencies. Significant changes in the spectral structure of the EMI current were noted at the three locations for frequencies above 20 MHz. The maximum and minimum values are dependent on frequency and the location of the probe. This indicates that standing waves similar to those found on antennas are present on the shield.

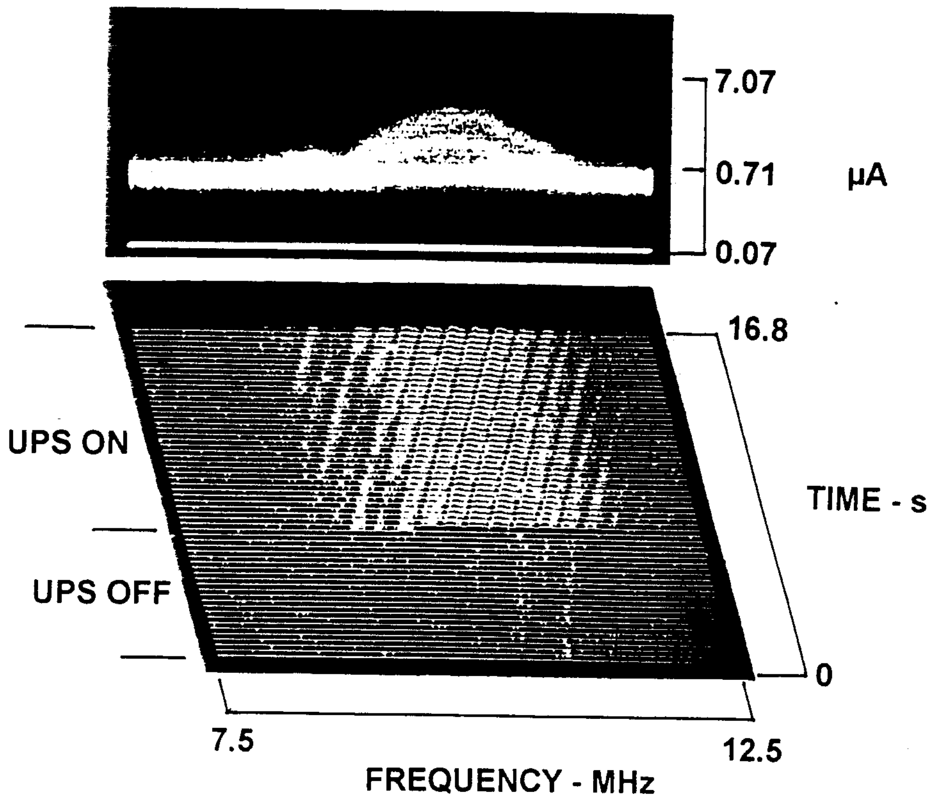
Figures 3-2 and 3-3 show EMI current flowing in the LAN cable near 10 MHz. It has a distinctive temporal structure. The slanting lines are typical of those from a switching device where the switching action is synchronized to the frequency of the power-line voltage waveform. This current was present when the computer was turned off, and it did not change in any significant manner when the computer was turned on. The source of this component of EMI current was traced to a small (1 kW) Uninterruptible Power Supply (UPS) providing power to a second desktop computer located in the room next to the test location. Figure 3-9 (960517 1023) shows the EMI current in the LAN cable when the UPS was on and turned off. Neither the UPS or its associated computer were directly connected to the building LAN system or the test computer; however, other possible interconnecting paths for the flow of EMI current, such as power conductors and grounds, did exist. The conducting path of the EMI current from the UPS to the shield of the LAN cable and its return back to the UPS source was not traced. This example shows that EMI current paths can be elusive, complex, and difficult to trace.



960517 0944
NPS, LAN Cable,
2", 23" and 45" from Computer
50 MHz, 100 MHz, 300 kHz, 200 ms
F-70, +20, 0, -40

Figure 3-8

EMI Current at Three Locations along the LAN Cable



960517 1023
NPS, LAN Cable, 2" from Computer
CPU OFF, MON OFF, UPS ON/OFF
10 MHz, 5 MHz, 30 kHz, 200 ms
F-70, +20, 0, -30
Bob Perry's UPS

Figure 3-9

EMI LAN Current from a Remote UPS

4. DISCUSSION

The desktop computer used in the tests described in this technical memorandum had been identified as a source of harmful levels of radio interference in a small receiving site prior to this investigation. The details of the mechanisms producing the radio interference were not understood when the computer was used at the receiver site. This investigation provided considerable insight into the mechanisms responsible for the radio interference.

The computer was an inexpensive 486-25 clone desktop with a with a metal base and a plastic cover. The design and construction of the computer was not unusual. It was considered to be a typical-low cost unit at the time of its purchase for field use, and it is typical of many computers still used in receiving and data-processing sites from the viewpoint of RFI/EMI problems. One might criticize the use of a computer with a non-metallic cover since the cover provided no significant shielding for the direct radiation of EMI from the primary components of the computer. In this case, when the computer was operated as a standalone unit, no significant EMI problem was noted. The dimensions of the computer, compared to the wavelength of the spectral components of RFI/EMI generated by the computer, were small enough that the unit did not radiate sufficiently to cause interference to the operation of a receiving site. This fact placed emphasis on the contribution of radiated fields from EMI current flowing on the electrically long conductors attached to the computer.

An attempt was made to simulate the actual installation of the computer as used in the field. While an identical installation was impossible to obtain, a reasonable simulation of its use was feasible. The cables and conductors attached to the computer were similar in length to those used in the field. EMI current injected into these conductors by the computer was considered to be a potential explanation of the problem encountered in the receiver site. Prior measurements by Signal-to-Noise Enhancement Teams had suggested reasonable limits for the maximum permissible EMI current that could be injected into the grounds, power conductors, cable shield and other conductors of a receiving and data-processing site. These limits[1] were used as guidelines during this investigation.

---

[1] Vincent, W.R., and Richard W. Adler, Technical Aspects of Grounds at Naval Receiving and Data Processing Facilities, Technical Memorandum SNEP950830, Naval Postgraduate School, Monterey, CA, 1995.

Ambient EMI current from other sources was found on the cables connected to the test computer before it was turned on. Since other computers and other digital devices (such as UPS units, printers, scanners, LAN networks, modems, etc.) are commonly used in small and large receiving sites, a certain amount of ambient EMI current is unavoidable. Harmful levels of EMI current in such conductors can sometimes originate from these other devices, and the ambient EMI current must also be low enough to be harmless to the primary mission of a receiving site, the detection and reception of radio signals.

In this case, the ambient current was almost acceptable, but the computer injected significant levels of EMI current onto the outer surface of the shield of the coaxial LAN cable and common-mode EMI current into the power wires. While the EMI current levels were similar on the keyboard cable, the short length and isolation of this cable from other conducting objects was a mitigating factor that minimized its impact on the receiving site. Extensions of a keyboard cable or the coupling of radiated fields from the keyboard cable to other conductors could change this finding.

The injection of harmful levels of EMI current into the power cables and onto the LAN cable shield was the primary reasons for the harmful levels of radio interference at the receiving site. This can be corrected (1) by the elimination of the cables (this would be difficult to achieve with the power cable, and it would result in the loss of a significant capability with the elimination of the LAN cable), or (2) the reduction of the EMI current levels on these and all other such cables to harmless levels by some means. Grounding the computer is not a feasible or an acceptable solution since the ground becomes another electrically-long conductor carrying EMI current.

Common-mode EMI current in the power conductors can be reduced by adding a filter to the black and white power conductors and appropriately terminating the green wire at the computer. The filter must be added at the outer case of the computer to be effective, and there must be a suitable return path for the EMI current to flow from the filter to its internal source.

The reduction of the EMI current on the outer surface of the shield of the LAN cable is a more complex matter. Most standard LAN cards drive the inner conductor against the shield of the LAN cables. This generates a potential between the shield of the LAN cable and the metal base of the computer. This potential results in harmful levels of EMI current on the shield. Its elimination requires that the LAN cable shield be grounded at the entrance of the cable into the computer. This would eliminate the potential difference between the computer and the cable shield, but most LAN cards are designed to operate with insulated and floating coaxial connectors. This is an undesirable feature of cabled LAN systems that cannot be tolerated in receiving sites.

Attempts to use ferrite slugs on the coaxial LAN cable to reduce the magnitude of the EMI current on the outer shield is, at best, only partially successful. Two factors prevent this from solving the problem. The first factor is the EMI current generated by other devices on the LAN system that would not be affected by ferrite slugs located at the test computer. Second, the driving impedance of the cable shield varies from low to high values over the frequency range of interest. Ferrite slugs can reduce the EMI current somewhat at the frequencies providing low driving impedance values but not at the frequencies generating high impedance values where potentials are high and current and its associated magnetic fields are low. The only known solution for a wired LAN system is to change the design of the LAN cards to eliminate the floating coaxial connector and apply this technique throughout the entire LAN system. The use of floating shields in LAN systems is a major cause of EMI problems in receiving sites. Another acceptable solution is to eliminate all wired or cabled LAN systems and replace them with fiber optic systems. Even then, care must be taken to avoid the use of fiber optic cable with conducting shields that are sometimes used for security or physical protection reasons.

5. CONCLUSIONS

A desktop computer was identified as the source of harmful radio interference to a receiving site. While the computer was the actual source of the EMI, it was electromagnetic radiation from cables and conductors connected to the computer (e.g., the power, LAN, ground, and telephone lines) that was the primary problem. Direct radiation from the computer was not significant even though the computer had a plastic cover. Eliminate the EMI current flowing on the conductors associated with the computer and the radio-interference problem will disappear.

Techniques are available to reduce EMI current injected onto such conductors to harmless levels. The Topographical Control of EMI described by J. Nanevicz and his associates at SRI International and the similar Integrated Barrier, Filter, and Ground techniques described by Adler and Vincent of the Naval Postgraduate School provide the basis for the control of this unwanted current. From a practical standpoint, there is no convenient handbook available to naval personnel describing a means to implement these techniques. The ability of naval personnel to combat the problem described in this paper is severely hampered by the lack of such a handbook.

Technical Memorandum
SNEP 9803
March 1998

The EMI ASPECTS OF GROUNDS AT RECEIVING AND DATA-PROCESSING FACILITIES

Prepared By:

Wilbur R. Vincent, Richard W. Adler, and Andrew A. Parker

Signal Enhancement Laboratory
Electrical and Computer Engineering Department
Naval Postgraduate School
Monterey, CA

INTRODUCTION

Grounds at receiving and data-processing sites have evolved over past decades into a confusing mixture of old concepts, new concepts, and a variety of physical configurations. Unfortunately, the literature available to site planners, managers, operators, equipment installers, and maintenance personnel is a hodgepodge of old, confusing, partly wrong, partly correct, and often conflicting information. There is no consistent or unified document providing a good understanding of facility grounds, why they are needed, how they function, and how to design them. This has resulted in considerable confusion about the best grounding technique, the best way to achieve a good ground system, the technical reasons for grounding, and especially the use of grounds to control site-generated EMI problems.

A number of names are used to describe grounding systems. This proliferation of names adds to the confusion about grounds since the technical purpose of the names for grounds is seldom defined. A partial list of these names includes:

Single Point	Building
Multiple Point	Facility
-Equipotential	Room
Zero Potential	Electrical
NEC Green Wire	Power
Facility Green Wire	Neutral
Signal	Neutral-Ground Bond
Red	Earth
Black	Lightning
Computer	Antenna
Coax Shield	Building Structure
Cable Shield	Water Pipe

The confusion about grounds is in part generated by conflicting information and improper interpretation about the use of the traditional building or facility ground-bus system and the newer green-wire power ground systems dictated by the National Electrical Code (NEC). The newer NEC green-wire system was instituted partly because the impedance of the electrical fault loops of the older building bus systems was frequently too large to allow circuit breakers to trip. This serious problem was corrected by incorporating the green-ground wire into the power cords and building wiring, thus lowering the electrical impedance for the flow of fault current to acceptable levels. However, many of the concepts, opinions, and even valid reasons for the use of the facility ground system remain in the literature, and they are often poorly understood.

The grounding issue has been further clouded by the widespread use of power-control and other digital devices that impress high levels of EMI current onto grounds of all kinds, power conductors, and many other conductors of a facility. This current consists of spectral components of EMI current extending from low-order harmonics of the power system up to HF, VHF, and even UHF frequencies.

The primary purpose of this document is to provide technical information about the confusing and often misunderstood role of all types of grounds in the control of EMI. It is an update of a technical memorandum provided in 1995[1].

1 Wilbur R. Vincent and Richard Adler, Technical Aspects of Grounds at Naval Receiving and Data-Processing Facilities, Technical Memorandum SNEP 950830, Electrical and Computer Engineering Department, Naval Postgraduate School, August 1995.

This memorandum addresses the technical aspects of grounds, and it provides a technical basis for the evaluation of the usefulness and effectiveness of all ground systems. The role of the grounding in accordance with the NEC is briefly discussed. The role of the extra ground buses and conductors that supplement the NEC safety ground is discussed.

The scope of this document is limited to ground systems and conductors inside a receiving and data-processing site. It does not deal with the important aspects of antenna ground planes, lightning grounds, or with the requirements for the NEC earth ground.

THE NEC GROUND

The NEC handbooks provide accurate, concise, and useful descriptions of the "green-wire safety ground" and the "earth ground" required for the electric-power wiring of a receiving and/or a data-processing facility. Full compliance with the NEC is required at all CONUS sites, and it should be followed at all overseas sites. Full compliance with the NEC is supported by this document. There is no technical conflict between the NEC grounding requirements and the need to efficiently operate radio-receiving and data-processing systems. All sites should have the latest version of the NEC handbook[2] available to their management, engineering, and site-maintenance personnel to ensure that its requirements are fully met.

The NEC requires that a good earth ground be provided at the entrance of electric power into a facility, and the neutral-ground bond be established only at this point. It also requires the use of a third conductor (the NEC green-wire ground conductor) for all electrical loads and in all equipment power cords. These requirements are fully supported in this document; however, one must consider that the sole purpose of the NEC green-wire ground is for the safety of equipment and personnel. It has no other purpose.

<u>The NEC does not deal with the EMI aspects of grounds.</u> The impact of EMI on grounds must be dealt with as an additional aspect of any ground system. EMI current flowing in ground systems and on other conductors of a facility is now a <u>primary problem</u> affecting the performance of receiving and data-processing facilities. It is necessary to place additional, and specific, requirements on site equipment and on all ground systems to limit EMI current flowing on grounds and other related conductors (and its associated potentials) to harmless levels.

THOSE OTHER GROUNDS

Many of today's receiving and data processing sites have additional ground conductors and ground systems above those required by the NEC. They are often incorrectly called "signal grounds" or by other names seldom related to their modern role or purpose. They are called "facility grounds" in this paper. The role of these facility grounds and their impact on EMI problems are explored in this section.

---

2 National Electrical Code Handbook 1996, National Fire Protective Association, Batterymarch Park, Quincy, MA.

In addition to facility grounds, numerous additional conductors in a site are electrically tied to both the NEC and the facility-ground conductors. These additional conductors include:

Conduits	Water Pipes
Cable Trays	Sewer Pipes
Power Conductors	Security-System Conductors
Telephone Cables	Steel Beams
Communications Cables	Reinforcing Rod in Concrete
Cable Shields	Concrete
Air-conditioning Ducts	Cabinet Surfaces

The above conductors are often in direct electrical contact with both the NEC green-wire-ground conductors and facility-ground conductors. In addition to conduction paths, inductive-coupling and capacitive-coupling paths transfer EMI current from one conductor to other nearby conductors. The above examples of additional conductors are integral parts of the total ground system of a facility. They must be considered when dealing with the EMI aspects of a receiving and data-processing facility. They cannot be ignored.

All portions of all ground systems efficiently conduct EMI current and potentials throughout a site. The total value of this current remains constant from its source, throughout its path(s) in a site, and back to its source in accordance with Kirchhoff's laws of current flow. There is no reduction in the value of the total current flowing in the ground system of a site by any mechanism except for small losses due to electromagnetic radiation at the higher frequencies. Electric current flows from its source, and back to its source, in a loop without loss. The loop can include many parallel paths of varying lengths, routings, and electrical impedance.

THE PRIMARY GROUND PROBLEM

The primary problem with the facility ground system is the presence of harmful levels of EMI current flowing on the grounds. This current also flows on all those other conductors associated with grounds (the cable shields, conduits, pipes, air-conditioning ducts, etc.). EMI current flowing on grounds and those other conductors seeks a way to leak into signal paths where it becomes interference. No modification of the facility ground system will significantly alter the levels of the EMI current or fix the leakage points. It will only change, often to a minor extent, the paths for the flow of the EMI current. Simply decrease EMI current to harmless levels, and all grounding problems will disappear regardless of the type of ground system.

Since EMI current flowing on grounds (rather than the design of either the NEC or the facility ground) is the primary culprit, it is necessary to examine this issue in some depth. Field measurements have identified certain classes of equipment and types of leakage into signal paths as potential sources of harmful levels of EMI current. These are:

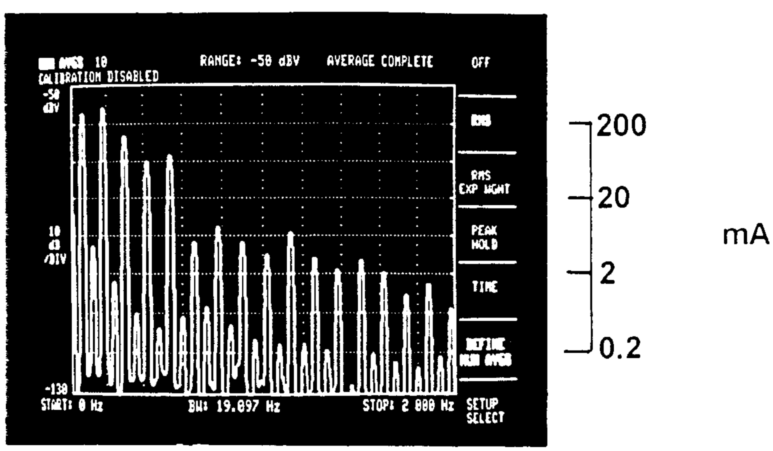
- Power control equipment employing solid-state switching devices.
  - Switching power supplies.
  - Variable-speed motor controllers.
  - Uninterruptible power supplies.

- Inadequately contained signal paths.
    - Cable shields penetrating inside equipment.
    - Use of insulated bulkhead connectors.
    - Improper assembly of connectors on signal-carrying cables.
    - Improper termination of cable shields.

Not all of the listed devices generate excessive EMI current on grounds and other conductors. Some well-designed devices do not inject excessive levels of EMI current onto grounds (and those other conductors) while other similar devices inject very high levels of current onto grounds and those other conductors. The specifier of such equipment must ensure that only those items that inject low and harmless levels of EMI current onto grounds are provided to the sites.

A few examples of harmful levels of EMI current on grounds, cable shields, and other conductors are provided to illustrate the problem. These examples are divided into two classes of EMI current for measurement convenience: low-frequency and high-frequency EMI current. In most cases both classes of EMI current will be present on grounds and those other conductors and must be considered while planning and operating an effective receiving and/or data-processing site.

The low-frequency EMI current is often, but not always, the low-order harmonic current generated by nonlinear power loads. Figure 1 (931215 1052) shows the low-order harmonic current generated by a variable-speed induction-motor controller which is injected onto the NEC green-wire ground of the power conductors feeding the controller.



931215 1052
GOR, 20400, Panel PU, mechanical room
Green wire (main panel)
CT5 (20:1), P6021 (10:1), 0

Figure 1
Low-Frequency EMI Current Generated by a Variable-Speed Air-Handler Motor Controller

The controller provides a means to vary the flow of air in the air-handling system of a building housing a large data-processing center. In this example, the controller injected 564 mA of current onto the green-wire ground at 60 Hz, 6.3 mA of current at 120 Hz, and 317 mA of current 180 Hz. The current at higher-harmonic orders can be read from the amplitude scale on the figure. This current was conducted from its source to the common green-wire ground terminal block in the power panel feeding the motor controller. It then was divided among other green wires, the power panel ground, metal air ducts, conduits attached to the power panel, and several other conductors. Since the motor controller was located adjacent to rooms containing communications cables and data-processing equipment, some of the current found its way onto the shields of cables carrying analog and digital signals. Eventually, this current returned to the motor controller over other conductors, and it sought ways to enter signal paths and corrupt both analog and digital signals.

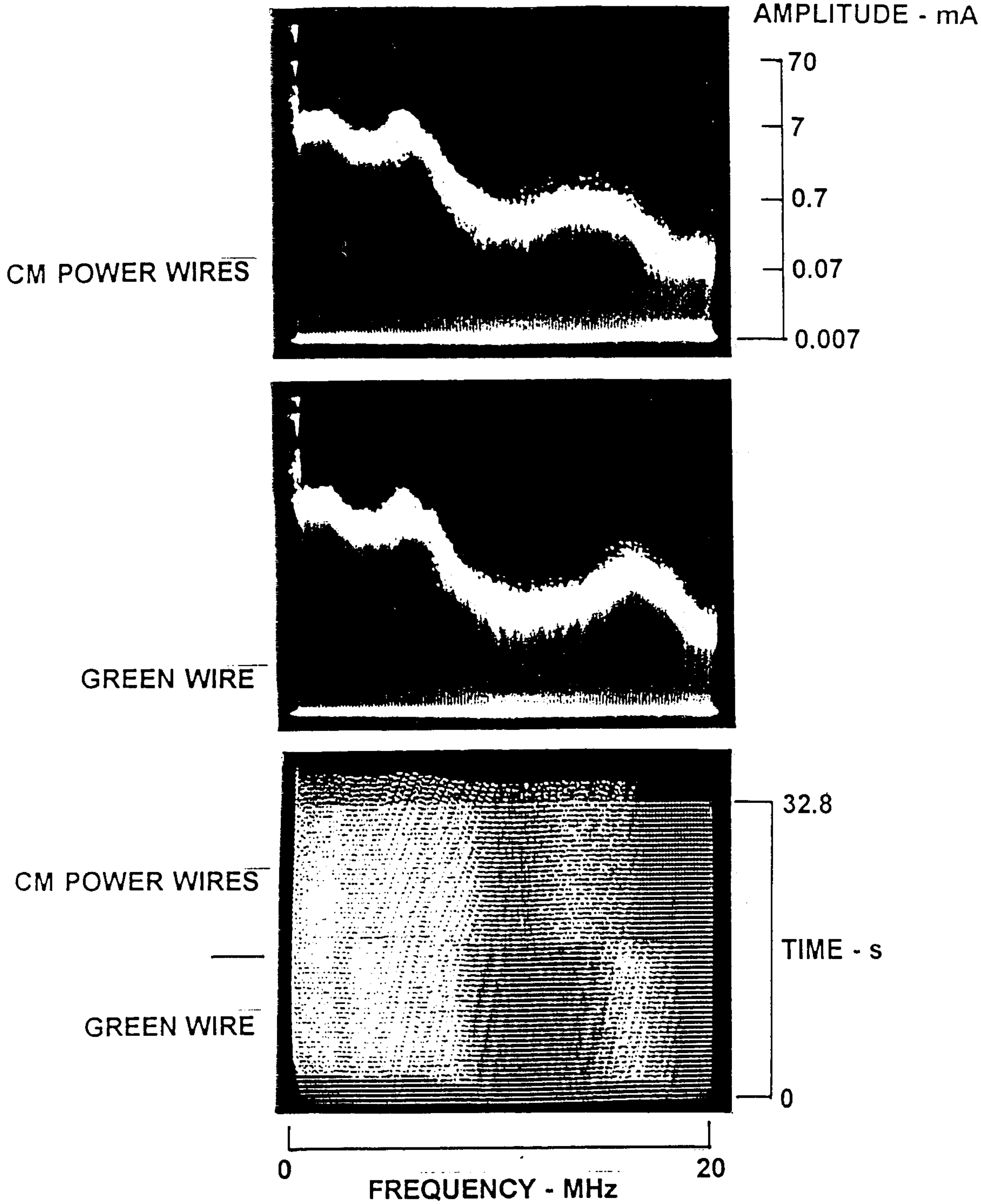
Figure 2 (931215 1351) shows the high-frequency EMI current flowing on the NEC green-wire ground of the same motor controller and the common-mode current flowing on all power conductors feeding the controller. The current probe used to obtain the data provided a flat response from 100 kHz to well over the upper frequency limit of the data. The upper amplitude-vs.-frequency view shows the spectral shape of the green-wire current, and the lower amplitude-vs.-frequency view shows the spectral shape of the common-mode current flowing on the power conductors. The time-history view on the bottom provides a means to compare the coarse-scale spectral and temporal structures of the two examples.

The current shown in Figure 2 was also carried to other parts of the facility over the power conductors carrying the low-order harmonic current. The level of the high-frequency EMI current was about 7 mA at a frequency of about 5 MHz. This is equivalent to the current flowing in an antenna from a low-power HF transmitter used for long-distance communications. This current is conducted, and capacitively and inductively coupled, onto other nearby conductors. This current adds to the low-frequency current shown in the earlier view. This current produces significant levels of voltage along conductors. This current is much higher than the signal current levels in nearby communications cables, indicating that significant levels of signal-path isolation are needed to avoid signal contamination.

The high-frequency EMI current has one additional aspect that must be considered. It results in standing waves of current and voltage along the conductors. These standing waves are identical in principle to those found on transmission lines and antennas.

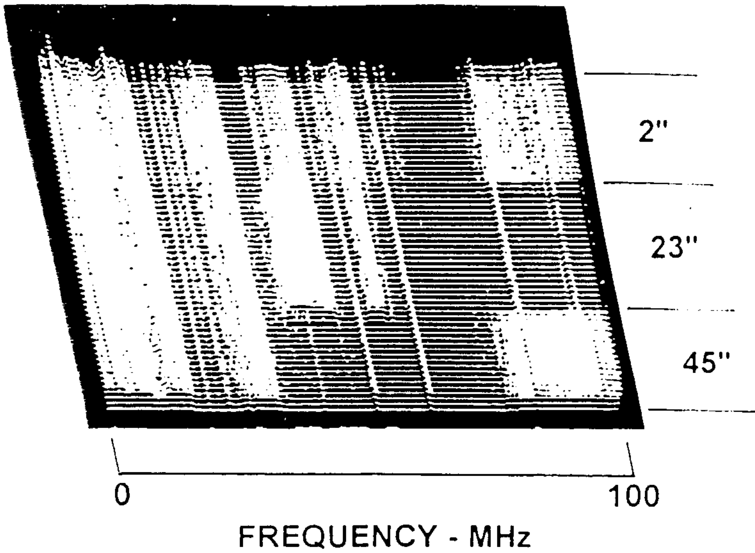
Figure 3 (960517 0943) shows a pictorial view of the spectral properties of EMI current injected onto the shield of a LAN cable at three different locations along the cable. The current was caused by signal leakage from an improperly designed and assembled LAN connector located on the rear of a standard workstation computer. Note that the low-frequency EMI current remained the same for the three measurement locations as anticipated since the electrical distance between the three locations was short compared to the relatively long wavelength of the low-frequency EMI current. When the distance between the measurement points became large compared to about 1/20 of a wavelength, the spectral content of the high-frequency EMI current changed considerably from one location to another. This observation verifies that standing waves of EMI current and voltage exist on the LAN cable shield at the higher frequencies of the broad-band EMI current. It also verifies that a single measurement of EMI current at the higher frequencies, especially narrow-band or discrete-frequency measurements, does not produce a complete understanding of the EMI current.

Figure 2
High-Frequency EMI Current Generated by a Variable-Speed Air-Handler Motor Controller



931215 1351
GOR, 20400, Mech Rm, AHU-2,
Green wire in on bottom; power in common mode
10 MHz, 20 MHz, 30 kHz, 500 ms
F70. 0, -30, -10

Figure 2
High-Frequency EMI Current Generated by a Variable-Speed Air-Handler Motor Controller



960517 0943
NPS LAN Cable
50 MHz, 100 MHz, 100 kHz, 200 ms
F-70, +20, 0, -40

Figure 3
Pictorial View of Changes in EMI Current Along the Shield of a LAN Cable

To further investigate the standing wave issue, EMI current at a sequence of discrete frequencies was injected onto the heavy copper ground bus running under a row of cabinets at a receiving and data-processing site. A broad-band injection probe was used to supply the current, and a nearby measurement probe was used to measure and set the level of the injected current. The amplitude of the injected EMI current was set to a value typically found on ground buses. The frequency of the injected current was varied from 2 to 30 MHz, and the current at other locations along a facility ground bus and on ground conductors attached to the ground bus was measured.

Figure 4 provides the physical layout of the current-injection and measurement configuration. The injection probe is shown at the left side of the figure and three measurement probes on the right side of the figure. The measurement probe in Bay 9 was placed on a cabinet ground wire which ran from an internal cabinet bus down to the facility ground bus. The measurement probe under Bays 8 and 9 was placed on the heavy copper ground bus. The measurement probe under Bay 8 was placed around the flexible Liqua-Tite™ conduit containing the power conductors for Bay 8. The Liqua-Tite™ conduit was connected to the cabinet ground inside the cabinet and to the sheet metal power-cable raceway. Four identical sets of instrumentation allowed the current to be set at the injection location and to be read simultaneously at all measurement locations.

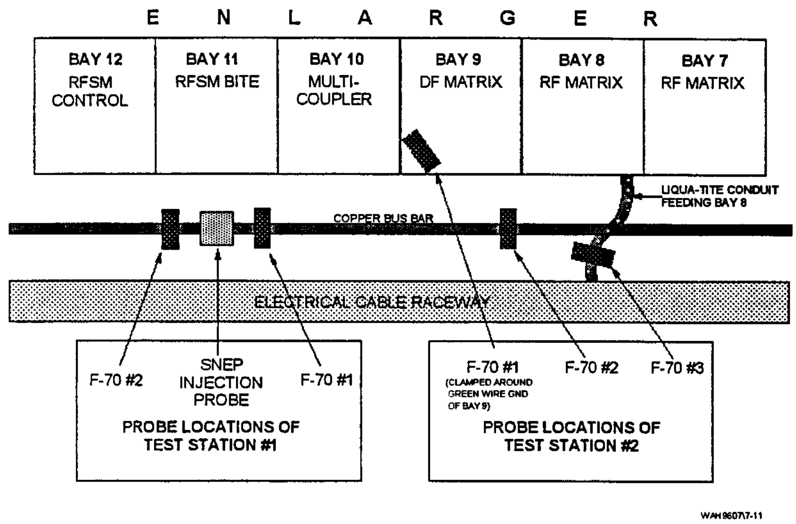


Figure 4
Measurement Configuration

Figure 5 shows how the current at the three measurement locations changed as frequency was varied. The injection current was held constant for all measurements. At low frequencies the measured ground current was considerably less than the injection current. Some of the injected current found conducting paths along other conductors attached to the facility ground bus and on inductive and capacitive coupling paths to other conductors. Near 15 MHz, the current on the ground bus to Bay 9, and the current on the main bus (about 6 feet from the injection probe), started to rise.

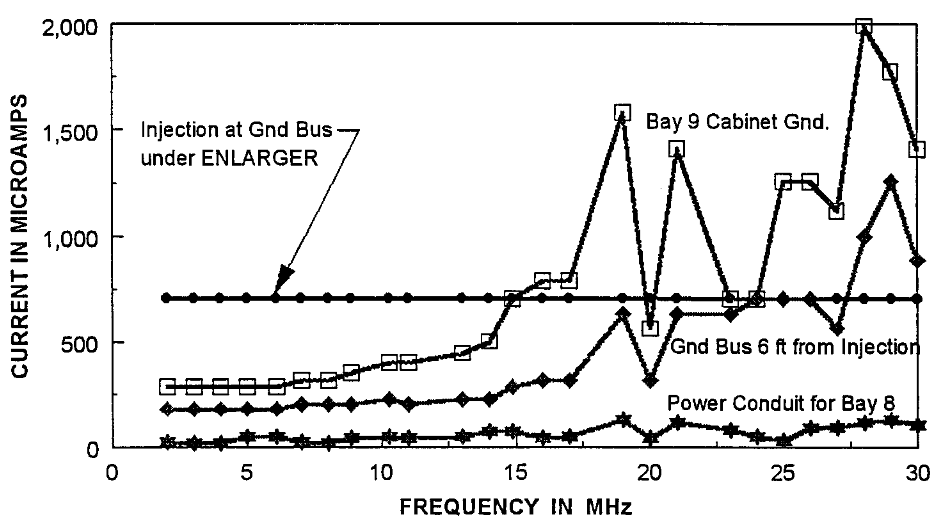


Figure 5
Ground Current VS. Frequency at Three Locations

As frequency was further increased, the measured current exceeded the injected current and eventually reached very high values compared to those at the lower frequencies. Resonance conditions and standing waves are indicated by the peaks and nulls in the current. This implies that the voltage induced by the current also had peaks and nulls. The voltage peaks are at the current nulls and the voltage nulls are at the maximum values of the current.

The current on the Liqua-Tite™ conduit did not increase in a manner similar to that measured by the other two probes. This is attributed to the increased inductance of the spiral ground conductor embedded in the flexible Liqua-Tite™ conduit. This inductance inhibits the flow of high-frequency EMI current, but it does not significantly affect the flow of the low-frequency EMI current.

The data dramatically shows that high-frequency EMI current at any discrete-frequency can vary by orders of magnitude along a ground or any other conductor. Under some conditions, this increase can enhance EMI leakage into signal paths. It can also produce high-amplitude transients from incidental contacts between conductors carrying EMI current. These transients also propagate along grounds and other conductors while seeking a way into any poorly contained signal path.

One additional item is provided to illustrate the coupling of EMI current from one cable shield to another. Current was injected onto the shield of a 250-foot long multiple-pair cable identified as Cable 1. Current was measured at 10-foot intervals along this cable. Figure 6 shows the standing waves measured along the length of Cable 1. A second shielded cable was run in parallel with Cable 1, and it is identified as Cable 2. Current inductively and capacitively coupled into Cable 2 was measured at intervals along Cable 2. The results are also shown in Figure 7. The amplitude of the standing waves on Cable 2 was about the same as those on Cable 1 although the nulls and peaks were displaced from those on Cable 1. This is because shield of Cable 2 was not terminated at either end, hence current could not flow at the ends of the cable.

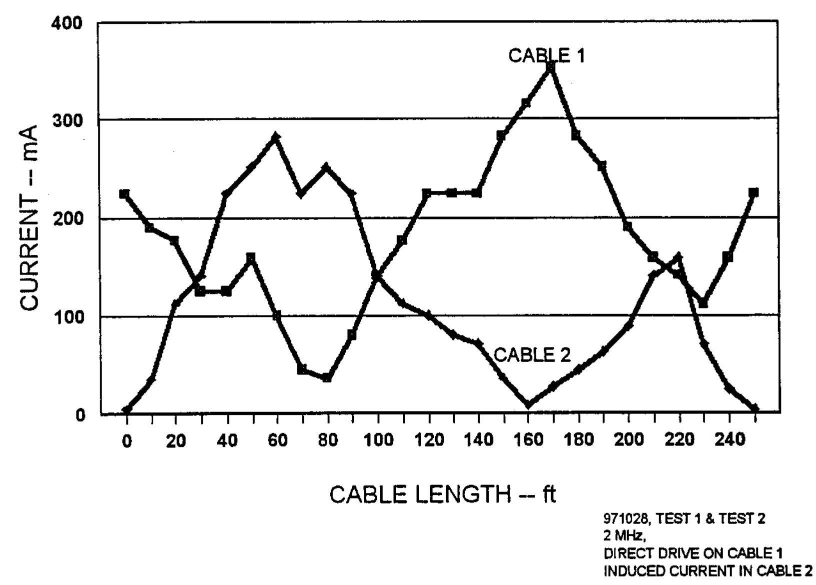


Figure 6
Coupling of EMI Current from One Cable Shield to Another Cable Shield

The results of the cable-to-cable measurements show that high-frequency EMI current is efficiently coupled to other nearby conductors including cables, grounds, power wires, conduits, cable trays, building structural material, pipes, and all other nearby conductors. Improving grounds will not alter this aspect of EMC in modern receiving and data-processing facilities. The only effective mitigation technique is to prevent EMI current from flowing on the conductors in a site. This can only be done by eliminating the sources of EMI current.

PURPOSE OF THE FACILITY GROUNDS

It is often difficult to obtain a valid reason or purpose for today's facility grounds from their designers and installers. In many cases these grounds are based on outdated grounding concepts and requirements. The secondary grounds are not signal-return or signal-reference grounds, they do not provide a path to earth to dissipate EMI current, they do not provide a means to limit or control EMI problems, and they do not provide a useful equipotential reference for modern digital systems or for radio-receiving systems.

The only valid use for facility grounds in modern receiving and data-processing sites is to provide an auxiliary safety-ground system, primarily for personnel safety. A secondary ground system can be used to maintain low-voltage differences from cabinet to cabinet and device to device at low-frequencies in case of a failure of the NEC green-wire ground or for instances of improperly connected electrical conductors. This is a valid reason to have and use a facility ground system.

Some proponents of facility ground systems, including the equipotential ground system, suggest that they provide an equipotential reference for data-processing systems. It is true that any facility ground can provide a low-potential reference at very low frequencies (or long wavelengths) compared to the electrical dimensions of the ground system. This means that any ground system, including equipotential ground systems, with a dimension larger than about 10 feet cannot provide an effective low- or equal-potential reference if harmful levels of EMI current are present at frequencies higher than about 1 MHz. Many modern digital systems, computers, power-conversion devices, and power-control systems impress significant levels of EMI current onto grounds and other conductors at this and much higher frequencies. Equipotential reference ground systems, or other ground systems, no longer provide an effective means to control the impact of EMI current and potentials, or transients, on receiving or data-processing systems. Their usefulness in receiving and data-processing sites for this purpose ended with the introduction of modern digital systems and switching power-control systems into the sites.

THE NEED TO LIMIT EMI CURRENT TO HARMLESS LEVELS

GENERAL COMMENTS

Since EMI current and potentials on grounds and other conductors is a major issue in many receiving and data-processing sites, means must be found to limit both to harmless levels. The problem is establishing the level where EMI current and potential become troublesome. This is not a simple task since it requires detailed knowledge of the susceptibility of systems and equipment to EMI current and potential. This is made difficult by the complex and broadband spectral and temporal properties of most cases of EMI current and voltage. It is furthermore made difficult by the generation of spectral components of EMI current and voltage up to and often beyond 100 MHz. In addition, receiving sites are usually more susceptible to EMI problems than data-processing facilities because of the need to protect extremely low levels of received signals from contamination. Because of this difference, the EMI current and voltage limits for receiving and data-processing sites are discussed in different subsections.

Many readers will note that we have digressed from the strict topic of ground conductors. This is because the primary problem at receiving and data-processing facilities is not the copper conductors of a ground system. The primary problem is unwanted current flowing in these conductors (and on those other ground conductors) and the potentials generated by this current. When this is recognized, the solution to grounding problems becomes evident. Keep the EMI current and potential on all grounds (and on those other ground conductors) at harmless levels.

Receiving Sites

Two primary problems have been identified in receiving sites. Radiation from EMI current can be received by a site's antennas. It can also enter the signal paths by leakage.

Radiation and conducting paths can exist from sources of EMI current to the ground screen and elements of a receiving antenna. In-band spectral components of EMI current appearing on the ground screen or the signal-collecting elements, of a receiving antenna will appear as signals at the input terminals of a receiver. For example, a spectral component of current flowing on the ground screen or an element of a receiving antenna at a level of 0.02 μA will appear as a signal about 10-dB above the noise floor of a standard HF, VHF, or UHF receiver operating at a 3-kHz bandwidth.

In addition to direct conduction paths onto parts of an antenna, the radio-frequency-distribution (RFD) system of a receiver site often has leakage paths. It is not feasible to build and maintain an RFD with perfect isolation. In order to maintain reasonable RF integrity, an RFD must use double-shielded coaxial cable, high-quality coaxial connectors, proper coax-connector-installation techniques, and the full shielding of all RFD components. Few RFD systems fully meet this need.

These two mechanisms require that any in-band EMI current injected onto any ground conductor, or any related conductor, not exceed a prescribed level. Measurements have shown that one can expect an isolation factor of about 500 between the EMI current injected onto a site's ground conductors and the level of current appearing on the ground screen or the elements of an antenna for a large receiving site. This factor is reduced to about 100 for a small receiving site. Thus, the upper limit of in-band EMI current in a site's conductors is about 10 μA for a large site and about 2 μA for a small site. These are approximate factors, and they can be more or less depending on the physical layout of a site and the leakage of EMI in the RFD.

Other leakage mechanisms must be considered in determining the EMI susceptibility of a receiving site. Out-of-band EMI current flowing through nonlinear junctions in conductors can produce harmonics and in-band IM products. Such in-band spectral components must be held below detectable limits. Examples of nonlinear junctions are:

- Poor joints from brazing or welding of copper conductors.

- Joints produced by dissimilar metals.
- Welds on galvanized metal.
- Rusty or corroded joints.

Another condition producing in-band EMI from out-of-band EMI current is transients produced by incidental contacts between two bare conductors carrying broad-band EMI current. Limits must be placed on out-of-band EMI current as well as the in-band current to prevent bursts of noise from adversely affecting receiving systems. Examples of incidental contacts that have been demonstrated to produce transient interference to radio receivers and data-processing systems are:

- Metal objects rubbing against antenna elements or ground screens.
- Ground conductors rubbing against air-conditioning ducts.
- Ground conductors rubbing against conduits.
- Ground conductors in contact with each other.
- Two conduits lightly touching each other.
- Wires supporting lights and other fixtures touching conduits or other metal.

Suggested limits have been established for EMI current injected into ground conductors and all other related conductors of a receiving site. These limits are provided in Table 1. They have been verified by extensive field measurements at a number of receiving and data-processing sites by US Navy Signal-to-Noise-Enhancement Program (SNEP) Teams.

Table 1
Suggested Maximum Permissible Limits for Conducted EMI Current

Large Receiving Site

Frequency Range	Maximum Current
0 to 10 kHz	2 mA
100 kHz to 100 MHz	10 μA

Small Receiving Site

Frequency Range	Maximum Current
0 to 10 kHz	2 mA
100 kHz to 100 MHz	2 μA

The maximum limit between 10 kHz and 100 kHz can be established by linear extrapolation from one limit to the other. These limits have been established largely by measurement at a number of receiving sites. They are reasonable limits, but they may change as more data is accumulated and better models are obtained for the impact of EMI on receiving systems.

Data-Processing Sites

While suggested maximum levels of EMI current have been provided for a receiving site, similar suggested levels for a data-processing site have not been established. This is because there is no practical susceptibility model for digital signal paths, or a sufficient database on which to provide such values. While digital signal formats are well established and defined, the leakage mechanisms for EMI current to enter the signal paths of a site and adversely impact digital signal-detection processes are not well controlled or defined. The widespread use of insulated bulkhead coaxial connectors, the old habit of grounding a cable shield only at one end, the use of telephone punch blocks to control and reroute signal paths, and other poorly contained signal-path techniques all contribute to EMI leakage into cables and equipment and the accompanying signal-contamination problems. These kinds of problems (along with the wide- spread and uncontrolled use of devices which impress high levels of EMI current on cable shields, grounds and other conductors) are the primary problems in today's data-processing facilities. Correct them and EMI and ground-related issues will disappear.

The lack of understanding of EMI source mechanisms and EMI leakage mechanisms has led to the widespread use of fiber optic communications paths. The use of fiber cable (without a conducting shield) sidesteps and avoids many EMI problems. This is a partial and excellent solution to the grounding and EMI confusion that exists in today's data-processing sites.

THE ROLE OF EARTH GROUND IN THE CONTROL OF EMI

A number of documents suggest that EMI current can be drained and dissipated into an earth ground. Prior comments in this document have hinted that this is not possible. A more careful examination of the situation shows that EMI current flows from a source through a complex maze of parallel conductors and returns back to that source over the conductors of a facility, *including those other conductors*. There is some minor loss due to radiation effects. Unfortunately, EMI current is not diverted and dissipated into some magical absorbing region such as the earth.

The EMI current paths in a site almost always include both conductive and near-zone inductive and capacitive paths. The resistive and impedance components of EMI current paths that include earth ground are always higher than paths through the maze of ground conductors, power wires, cable shields, and other conductors. This means that little or no EMI current will ever flow into an earth ground. This has been verified by measurement. Thus the quality, type, and number of earth grounds is not a significant factor in the control of EMI problems in a receiving and data-processing site. The suggestion that earth grounds aid in the control of EMI is unfortunately a myth.

A good earth ground is required and necessary for power-safety, equipment-safety, and personnel-safety reasons. This requirement is covered by the NEC handbooks. At many sites, good earth grounds are required for protection from lightning. Some antennas require a good conducting ground plane. These separate and special requirements are not addressed in this document.

WHAT IS THE BEST GROUND SYSTEM?

Site designers, managers, operators, and maintenance personnel often inquire about the best ground system for a receiving and data-processing site. This document has, so far, carefully avoided identifying the best ground system. There is good reason for this care. There is no ground system that will aid in the prevention, control and correction of EMI problems. In general, the more extensive the ground system, the higher will be the EMI current because lower impedance paths will exist for its flow. This adverse aspect of improved and extensive ground systems must be taken into account when revising or modifying existing ground systems, or when installing new ground systems.

Large amounts of money are often spent on extensive and special ground systems. Expensive equipotential ground systems are sometimes touted as necessary, effective, and a cure for EMI problems. This approach is ineffective, and it always results in wasted time and money. The best ground system is a combination of (1) the NEC green-wire ground and (2) the least-costly secondary-ground system that will provide an effective personnel-safety, equipment-cabinet, and large-component ground. One additional factor must be considered. No ground system (or those other related conductors) must be allowed to carry harmful levels of EMI current throughout a site.

Since facility grounds are not a solution for EMI problems in receiving and data processing sites, other means must be used to solve EMI problems. This can be accomplished by preventing harmful levels of EMI current from being injected into grounds, power wires, cable shields, and other conductors of a site. The only practical solution to EMI problems is to block the injection of harmful levels of EMI current into grounds and other conductors at its source. This is the old-fashioned way of correcting EMI problems, but it is effective. *Integrated barrier, filter, and grounding* techniques applied to the enclosures of each source of EMI prevent the escape of harmful levels of EMI current outside the equipment enclosures.

CONCLUDING REMARKS

Many outmoded ideas and concepts still exist about grounds and their relationship to personnel safety, equipment protection, and the control of EMI. This paper provides some of the answers to these topics. Admittedly, some of the material conflicts with that provided in many published articles, specifications, training material, handbooks, and other documents. Yet the information is the product of many years of evaluating and correcting grounding and EMI problems in a large number of receiving and data-processing sites. All of the concepts presented have a solid technical basis, and they have been used for the successful solution of a large number of field problems. Only three items are important in the design and installation of an effective ground system. These are:

1. Comply with all aspects of the National Electrical Code.

2. Prevent harmful levels of EMI current from flowing on the grounds, cable shields, power conductors, and all those other associated conductors of a facility.

3. Eliminate all leakage points in signal-distribution cables and systems.

NPS-EC-01-007

NAVAL POSTGRADUATE SCHOOL
Monterey, California

Conducted EMI from an Engineering Model of a DC-to-DC Converter

by

Andrew A. Parker
Richard W. Adler
Wilbur R. Vincent

June 2001

Prepared for: ECE Department, Naval Postgraduate School

NAVAL POSTGRADUATE SCHOOL
Monterey, California

RADM DAVID R. ELLISON
Superintendent

R. Elster
Provost

This report was prepared by the Department of Electrical and Computer Engineering.

Distribution authorized to U.S. government agencies and their contractors; (operational system); (Dec. 1999). Other requests for this document must be referred to Superintendent, Code 0052, Naval Postgraduate School, Monterey, CA 93943-5000 via the Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Ft. Belvoir, VA 22060-6218.

The report was prepared by:

ANDREW A. PARKER
Research Associate
Department of Electrical and
Computer Engineering

Reviewed by:

JEFFREY B. KNORR
Chairman
Department of Electrical and
Computer Engineering

Released by:

DAVID W. NETZER
Associate Provost and
Dean of Research

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
June 29, 2001

3. REPORT TYPE AND DATES COVERED
Technical Memorandum, 15 Apr-15 Jun 2001

4. TITLE AND SUBTITLE
Conducted EMI from an Engineering Model of a DC-to-DC Converter

5. FUNDING NUMBERS

6. AUTHOR(S)
Andrew A. Parker, Richard W. Adler, Wilbur R. Vincent

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Electrical and Computer Engineering
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER
NPS-EC-01-007

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of Electrical and Computer Engineering
Naval Postgraduate School
Monterey, CA 93943-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The views expressed in this report are those of the author and do not reflect the official policy or position of the Department of Defense or the United States Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution authorized to U.S. government agencies and their contractors; (operational systems); (Dec. 99). Other requests for this document must be referred to Superintendent, Code 0052, Naval Postgraduate School, Monterey, CA 93943-5000 via the Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Ft. Belvoir, VA 22060-6218.

12b. DISTRIBUTION CODE
D

13. ABSTRACT (Maximum 200 words)

The conducted EMI of an Engineering Model of a DC-to-DC Converter for shipboard power conversion in low and high frequency bands is presented. Characteristics of conducted EMI on control power, input, and output converter cables at various power levels are considered and compared with conducted EMI limits for land based radio receiving sites. Considerations for scaling up the design for shipboard applications is presented.

14. SUBJECT TERMS
Power Conversion, COTS, DC-to-DC Converter, EMI

15. NUMBER OF PAGES
33

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

STANDARD FORM 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

PREFACE

The data and results described in this document were obtained from an experimental model of a DC-to-DC converter whose operation is based on modern solid-state switching techniques. The converter was designed and constructed to explore the general performance characteristics of such devices and to examine their potential for shipboard operation. This aspect of the converter is not covered in this document. The design and operational properties of the converter will be described in a thesis being prepared by LT Bryan D. Whitcomb, USN as one of the requirements for a Masters Degree in Electrical Engineering at the Naval Postgraduate School, Monterey, CA. The data in this report supplements the purpose and objectives of the thesis project of LT Whitcomb.

The data in this document was obtained for a number of reasons including:

- to add to our data base on the EMI characteristics of solid-state power-conversion equipment,
- to obtain preliminary data needed to evaluate the impact of EMI from such devices on other shipboard systems,
- to obtain additional data needed to develop preliminary scaling rules to predict the levels of EMI current and power from higher-power converters,
- to develop EMI mitigation techniques for power-conversion devices, and
- to aid in the design and operation of future such power-converter equipment.

The authors of this document are grateful for the frequent operation of the DC-to-DC converter by LT Bryan D. Whitcomb and for guidance from his thesis advisors, Professors Robert W. Ashton and John G. Ciezki.

Andrew A. Parker
Richard W. Adler
Wilbur R. Vincent

SUMMARY

While solid-state power-conversion devices provide an exceptional capability to modify and control the electrical power provided to a variety of loads, they also can produce unwanted electromagnetic interference to other equipment and systems. This report provides the results of a series of measurements of the conducted EMI current generated by an experimental model of a DC-to-DC converter operating up to a maximum power level of 8 kW. The conducted EMI current was examined on all conductors penetrating the housing of the converter over the frequency range of 100 Hz up to 50 MHz under a variety of operating conditions. Wide-band measurement techniques were used to obtain the levels of impulsive noise generated by the converter, and a bandwidth-scaling curve is provided to convert the measured data to other bandwidths.

The converter produced excessive levels of EMI current on all conductors into and out of its housing. The conductors included the 120-VAC power wires providing power to its digital controller, the green-wire safety ground of the 120-VAC power cable, and the DC conductors into and out of the converter. Unwanted current on these conductors included harmonics of the 120-VAC power, the fundamental and harmonics of the switching rate of the converter, and higher-frequency components up to and above 50 MHz. The levels were sufficiently high that harmful levels of interference would result to nearby radio receivers operating in the VLF to low VHF frequency range. In some cases harmful interference would affect the operation of data-processing systems operating with power, grounds, and data lines located near the conductors of the converter.

The test results, when combined with similar data from other power-conversion devices, provide data useful in developing preliminary scaling rules to predict levels of EMI current that can be expected from higher-power converters.

The converter was designed and constructed generally in accordance with standard COTS equipment practices. Electromagnetic interference mitigation techniques were not used in its design. While standard electromagnetic interference reduction devices and techniques are available for such equipment operating at power levels up to about 100 kW they are not normally used in COTS power-conversion devices because of increased cost and the added complexity associated with the use of such techniques. In addition COTS interference reduction devices are not available for higher power levels.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

An engineering model of a DC-to-DC converter was designed and constructed as a thesis project at the Naval Postgraduate School[1] to explore the operational characteristics and performance of such devices. The engineering model was rated at 8 kW, and it was tested up to this level. The design characteristics and the electrical performance of the model will be described in the student's thesis. This document provides additional information about the levels of conducted electromagnetic interference (EMI) generated by the engineering model.

The possibility that a DC-to-DC converter based on solid-state-switching technology would generate harmful levels of conducted and radiated interference was recognized during the design and testing stages of the effort, however little documentary information about this aspect of such devices is available. The concern about EMI was supported by the finding that harmful levels of interference to radio-receiving and data-processing systems had been encountered from power-conversion devices employing similar switching techniques. For example, motor-controller to motor-controller interference from excessive levels of EMI current on power conductors has been identified in commercial establishments. Variable-frequency drives (VFD) for induction motors, uninteruptible power supplies (UPS), and some switching power supplies have produced harmful levels of radio interference at radio receiving sites. In addition interference from VFDs and switching power supplies has been found to disrupt the operation of computers and digital data-processing devices.

These concerns led to an examination of electrical and EMI specifications for such devices. Most commercial off the shelf (COTS) power-conversion devices are now manufactured and procured in accordance with the Federal Communications Commission (FCC) Class A EMI requirement[2] (a EMI level established for devices intended for industrial use) or other similar requirement. A more stringent FCC Class B requirement is used for devices produced for residential use, but very few COTS power-conversion devices meeting these stricter requirements are available. There is no similar category that applies to shore or ship installations containing radio and data-processing systems.

The reduction of EMI current flowing on conductors associated with its source to harmless levels has been found to be the only practical solution to the problem. This requires that the maximum tolerable levels of current be determined. Prior work by staff members of the Naval Postgraduate School provides reasonable maximum EMI current values at land-based sites[3], but no equivalent information is available for ships.

Section 2 of this report describes the test setup used to measure the levels of EMI current on conductors exiting and entering the engineering model of the DC-to-DC converter.

[1] Bryan D. Whitcomb. ***Design and Implementation of a High Voltage Power Resonant DC-to-DC Converter Module for a Reduced Scale Prototype Integrated Power System***, Draft of MS Thesis, Naval Postgraduate School, Monterey, CA, May 2001.
[2] 47CFR15.109 , ***Code of Federal Regulations, Federal Communications Commission Rules.***
[3] Wilbur R. Vincent. Richard W. Adler, and Andrew A. Parker, ***The EMI Aspects of Grounds at Receiving and Data-Processing Facilities***, Technical Memorandum SNEP 9803, Naval Postgraduate School, Monterey, CA, March 1998.

Section 3 discusses the implications of the results of the effort. A summary of the findings is provided at the beginning of the report.

Two photographs of the converter are provided to show the general configuration and the simplicity of the unit. Figure 1-1 shows a photograph of the front and top of the DC-to-DC converter. The top cover has been removed to show the internal components. The coaxial connectors on the right side of the front panel are monitor points. The switch near the center of the panel is for the 120-VAC power for the converter control circuits, and the vertical circuit board near the front of unit contains the components of the converter's control circuits. The 120-VAC and the DC power connections are located on the rear panel along with the cooling fan.

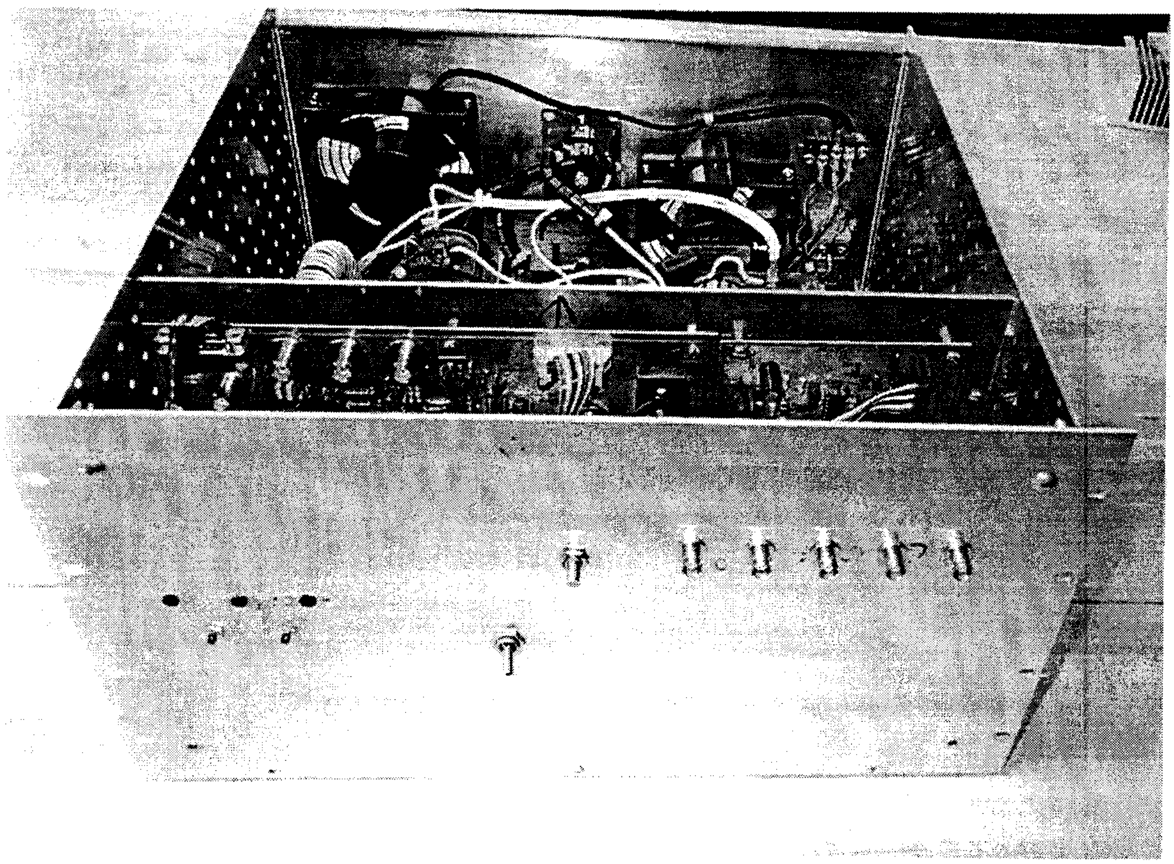


Figure 1-1

Front View of Converter Unit

Figure 1-2 shows a top view of the DC-to-DC converter. The components for the control circuits are on the vertical board located just behind the front panel, and the components used for the switching and conversion of electrical power from one level to another level are located in the rear compartment of the converter. A large vertical aluminum plate separates the control circuits from the switching and power-conversion components.

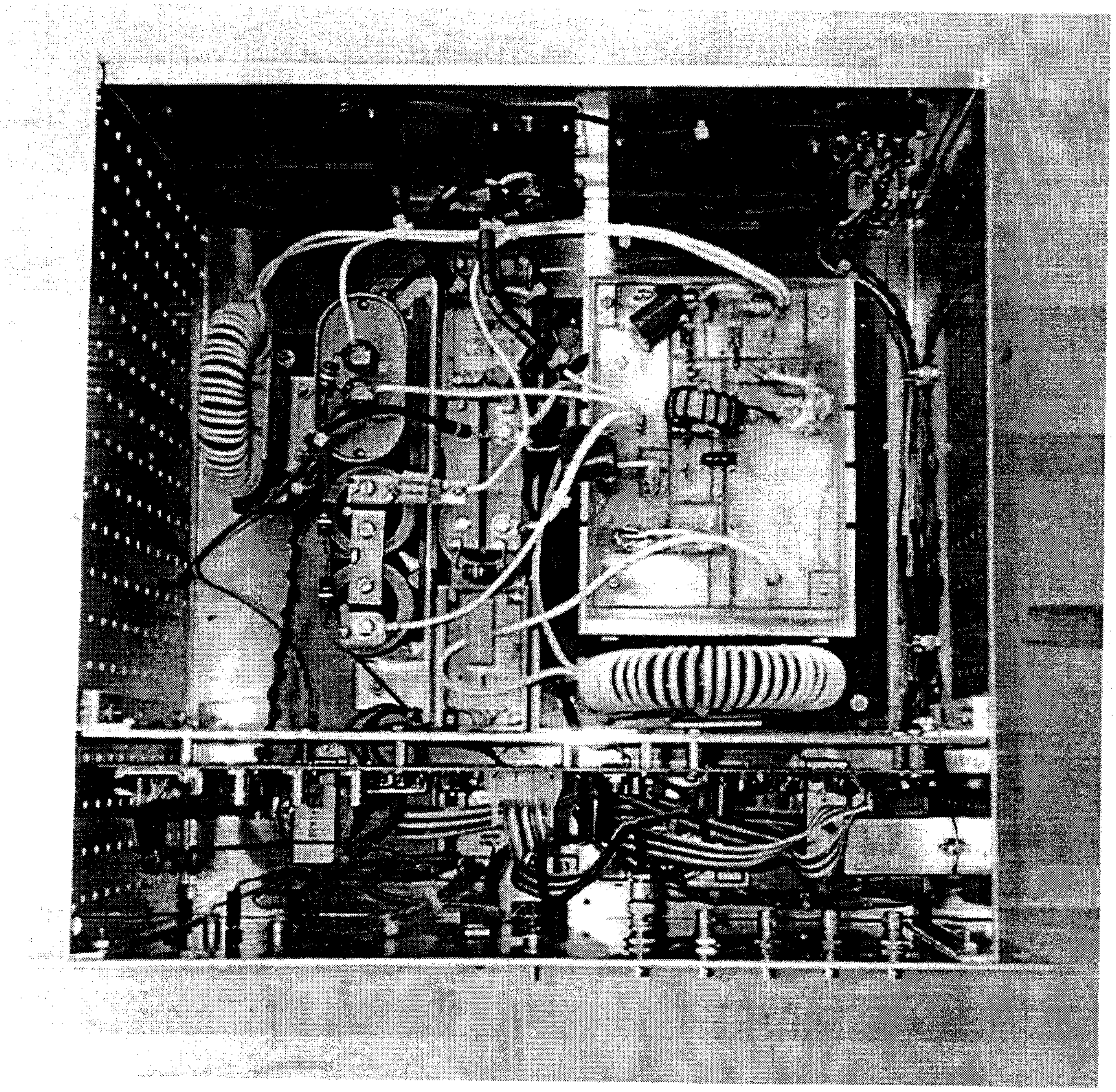


Figure 1-2

Top View of the Converter Unit

2. TEST SETUP

Two instrumentation configurations were used to measure the levels of conducted current flowing on conductors entering and exiting the DC-to-DC Converter. The first was a low-frequency instrumentation configuration covering the frequency range of 10 Hz to 100 kHz. The second was a high-frequency measurement configuration covering the frequency range of 50 kHz to 100 MHz. Some overlap in the frequency range was provided to permit a careful examination of spectral components of current at and near the transition frequency of the two test configurations.

Both instrumentation configurations provide a means to measure the spectral components of current over wide frequency ranges using standard current probes. Broadband current measurements were considered sufficient for the purposes of this preliminary investigation. All current measurements were calibrated in amperes.

While broadband electric-field probes are available for voltage measurements, they were not used for this preliminary effort. Voltage measurements would have provided the additional information needed to estimate the EMI power in individual spectral components and in larger portions of the spectrum, but this information was not necessary to assess the general nature of the EMI aspects of the system being tested.

2.1 Low-Frequency Instrumentation

Figure 2.1-1 shows a block diagram of the instrumentation used for the low-frequency (LF) measurements of EMI current.

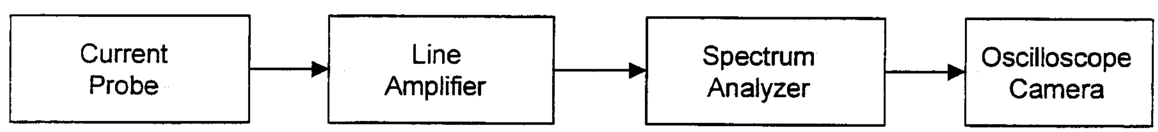


Figure 2.1-1

Block Diagram of Low-Frequency Instrumentation

A Tektronix Model CT-4/P6021 Current Probe with termination unit was used to measure low-frequency current over the range of 10 Hz up to 100 kHz. While this probe has a much higher design frequency limit than implied by the values stated, the exceptionally high dynamic range of the EMI current generated by power-conversion devices prevents using the probe and the low-frequency instrumentation for measurements at frequencies above 100 kHz. The probe response is flat over the frequency range of 200 Hz up to and above 100 kHz, and amplitude correction factors were used to determine the magnitude of spectral components of current below 200 Hz. These factors are -7 dB for 60 Hz, -4 dB for 120 Hz, and -1 dB for 180 Hz.

A WRV Model A-101A Line Amplifier was provided should the amplitude of any measured value of current fall below the sensitivity level of the spectrum analyzer. This amplifier is flat in response over the frequency range of 10 Hz up to the maximum frequency range of interest, and it provides gain in 10-dB steps up to 40 dB. The amplifier is battery operated to avoid possible noise coupling from ambient EMI on the 120-VAC power system.

A Hewlett Packard Model 3561A Spectrum Analyzer was used to measure the level of spectral components of current. It has sufficient resolution to allow the measurement of the levels of harmonics of the power frequency and other spectral components. While the analyzer provides an excellent capability to measure spectral components which are time stable, its low and fixed transform rate of 10/second is not sufficient to define the spectral and temporal properties of transients or components that rapidly change in amplitude or frequency with time. A Nicolet Model UA500A analyzer was available to investigate the properties of transients and time-varying components.

A Tektronix Model C-5C Oscilloscope Camera was used to record the spectral components of current over any portion of the frequency range of the instrumentation on Polaroid Type 667 film. Examples of photographs showing the measured amplitude of the spectral components of current are provided later in this report.

A small table accompanies each item of LF data obtained from the DC-to-DC converter. This table contains pertinent instrumentation settings and other measurement parameters. This information is required to identify each item of data and provide absolute scales for the data. The parameters of the table for the LF data are:

Line 1	Date in yymmdd format and local time
Line 2	Location, laboratory ID, measurement location
Line 3	Converter type, converter operational mode
Line 4	Conductor ID, main probe, secondary probe, line amplifier gain
Line 5	Additional comments

2.2 High-Frequency Instrumentation

Figure 2.2-1 shows a block diagram of the instrumentation used for high-frequency (HF) measurements of EMI current.

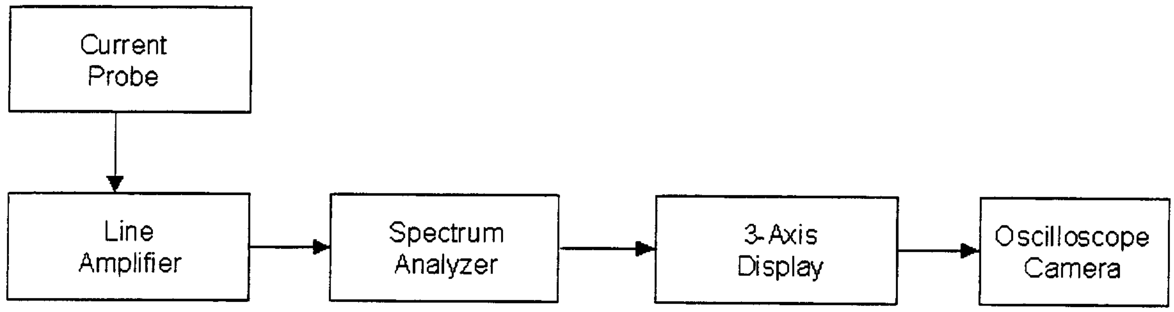


Figure 2.2-1

Block Diagram of High-Frequency Instrumentation

A Fischer Model 70 Current Probe was used for all high-frequency measurements. The probe is flat in frequency response over the frequency range of 100 kHz up to 100 MHz. Calibration curves are used to obtain the amplitude of spectral components of current from 50 kHz up to 100 kHz. A calibration curve for the lower-frequency range provides an overlapping frequency-measurement capability with the LF instrumentation.

A preamplifier assembly based on an Olektron Model B-HIA-20-HF Amplifier was used as a line amplifier for cases where the sensitivity of the spectrum analyzer was insufficient to measure low current levels.

A relatively old Hewlett Packard Model 141 Spectrum Analyzer was used to obtain the amplitude of spectral components of EMI current over the 50-kHz to 100-MHz frequency range. This older model analyzer provides significant advantages over newer analyzers. First it is a rapid scanning analyzer which proves to be highly useful in determining the temporal shape of transients and time-varying signals. Next, its blanking time is considerably shorter than for most newer digitally-controlled models, and the relatively short blanking time significantly increases the ability to detect intermittent impulses and switching transients often hidden during the longer the blanking time of newer models. The ability to rapidly adjust analyzer control settings to cope with time-changing properties of EMI current also is of considerable value. Finally, this particular analyzer had been modified to provide an enhanced dynamic range over other similar instruments.

An ELF Engineering Model 7200B 3-Axis Display was used to portray the temporal and spectral structure of the EMI current.

A Tektronix Model C-5C Oscilloscope Camera was used to provide permanent records of any desired time visual presentation of the structure of examples of EMI current.